Modeling of Rotary Kiln for Sponge Iron Processing Using CFD package (ANSYS 13.0)

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CERTIFICATE

This is to certify that the thesis entitled, "**Modeling of Rotary Kiln for Sponge Iron Processing Using CFD package (ANSYS 13.0)**" submitted by **Tapash Ranjan Majhi** in partial fulfilment of the requirements for the award of Master in Technology Degree in Chemical Engineering with specialization in "Chemical Engineering" at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance. To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

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NOMENCLATURE

$\rho \rightarrow$ Density

$\varepsilon \rightarrow$ Surface emissivity

$\nabla \rightarrow$ Gradient

$\sigma \rightarrow$ Stefan-Boltzmann constant

$\Phi \rightarrow$ Flux at a boundary face

$A \rightarrow$ Surface area

$D_f \rightarrow$ Diffusivity of flux

$e_s \rightarrow$ Surface emissivity.

$E \rightarrow$ Activation energy

$f \rightarrow$ Elemental mass fraction

$h \rightarrow$ Heat transfer co-efficient

$H \rightarrow$ Enthalpy

$k_{eff} \rightarrow$ Effective thermal conductivity.

$T \rightarrow$ Temperature

$P \rightarrow$ Pressure

$S_h \rightarrow$ Source term

$q_{Conduction} \rightarrow$ Heat transferred through conduction.

$q \rightarrow$ Amount of heat transferred.

$\vec{V} \rightarrow$ Velocity vector

CHAPTER 01

INTRODUCTION

Sponge iron, also called **Direct-reduced iron** (**DRI**), is formed, when naturally available Iron Ore which is an oxidised form of Iron (magnetite (Fe_3O_4) or hematite (Fe_2O_3)) is reduced to its metallic form. This reduction process occurs below the melting temperature of both metallic iron and its oxidised form. Though this process is carried out at lower temperature than melting point so there is less volume reduction but a large amount material get eliminated during reduction reaction. Oxygen removal form iron ore creates lots of microscopic pores. This microscopic pores gives the iron an sponge texture as shown in fig. 1.1. Therefore it is in another sense known as sponge iron..

Fig 1.1. Image of a Sponge Iron Granule

STATUS OF STEEL PRODUCTION (in MT)

	India	China
Year 1952	1.5	1.5
Year 2005-06	43	340

Now in India nearly 283 DRI units have been operating over the states of Orissa, Jharkhand, Chhattisgarh, West Bengal, Karnataka, Tamil Nadu, Andhra Pradesh, Gujarat and Goa.

In the year 2006 - India produced - 13.9 million ton

Venezuela - 6.2 million ton

Iran - 4.3 million ton

Mexico - 4.5 million ton

As per the National Steel Policy issued by the Ministry of Steel – India will produce 110 million tons of steel by 2020. The requirement of Sponge Iron as metallic will be 30 million tons.

Projection for metallic requirement in Year 2010-11 we require Melting Scrap 14 million and DRI 18 million But availability of scrap is not likely to reach 11 million. So there is a huge requirement of sponge iron production.

Today India produce 13.9 million tons of sponge iron, out of which 4.2 million ton is gas based and remaining 9.7 million ton is coal based. India has a proven reserve of 410 million ton of high grade iron ore, another 440 million ton of high grade iron ore which will be established. India has total 9992 million ton of iron ore reserves [1]. India has sufficient non-coking coal through of high ash low fixed carbon grade. Coal is used as a reducent for sponge iron making in the furnace. The availability of scrap of required quantum is unlikely and therefore scraps needs to be replaced more and more by DRI. Local supply of scrap is diminishing as generation of scrap in India due to improvement of technology is getting continuously minimized. As per World Steel Dynamics (WSD) – the Global shortage of scrap will reach 68 million tons in the year 2010. That means the scrap price will go up and availability will be a problem. Due to soaring price of iron ore and coke, blast furnace is being set up in the countries where iron ore or coking coal is available. We must produce steel at a cheaper cost to remain competitive and control over domestic market. DRI based steel making is therefore the only answer.

Sponge iron, also called Direct-reduced iron (DRI),[2] is produced from direct reduction of iron ore (in the form of lumps, pellets or fines) by a reducing gas produced from natural gas or coal. The reducing gas is a mixture majority of hydrogen (H_2) and carbon monoxide (CO) which acts as reducing agent. This process of directly reducing the iron ore in solid form by reducing gases is called direct reduction. The porous structure of sponge iron clearly visible under optical microscope as shown in fig. 1.2.

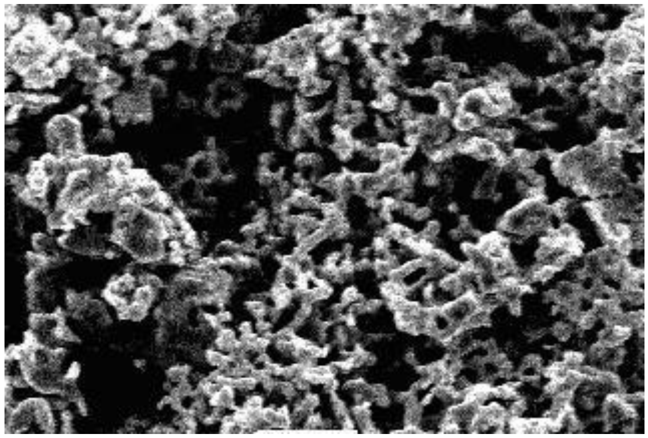

Fig1.2. Microscopic view of sponge iron[3]

Direct-reduced iron is richer in iron than pig iron, typically 90–94% total iron (depending on the quality of the raw ore) [4] as opposed to about 93% for molten pig iron. Due to its high purity it is an excellent feedstock for the electric furnaces used by mini mills. It allows them to use lower grades of scrap for the rest of the charge or to produce higher grades of steel. Due to following advantages sponge iron production is rising.

- Pelletized iron ore or natural "lump" ore are used in direct reduction process. Exceptionally in the fluidized bed process sized iron ore particles are used. Few selected ores are suitable for direct reduction process.
- Sponge iron is produced in a powdered form so, it acts as a good raw material that can very well mixed with other metals in the production of different types of iron-based or Ferro alleys.
- HDRI (Hot Direct Reduced Iron) is iron not cooled before discharge from the reduction furnace and immediately transported to a waiting electric arc furnace to be charged and thereby saving energy.
- Natural gas combined with little inert gases can be used in direct reduction process to avoid the need of removal of these gases for other use. Presence of any inert gas along the reducing gas lowers the effect (quality) of that gas stream and also the thermal efficiency of the process.

- Another most common uses for sponge iron is manufacturing of wrought iron. Iron of this type is useful in the creation of ornamental objects for use around the house, like decorative grills for screen doors, burglar bars for windows.
- Sponge Iron which is produced in power form can be made into pellets, which is an economic and useful substitute for the scrap metal sometimes used by steel manufacturers. The amount of time and resources required to produce sponge iron is minimal, so it is possible to manufacture large amounts quickly, a fact that only adds to the advantages of this type of iron product.

Direct reduction, is most commonly practiced alternative route of iron making, has been developed to overcome some of these difficulties of conventional blast furnaces. DRI is successfully manufactured in various parts of the world through either natural gas or coal-based technology. Iron ore is reduced in solid state at 800 to 1,050 °C (1,472 to 1,922 °F) either by reducing gas (H_2+CO) or coal. The specific investment and operating costs of direct reduction plants are low compared to integrated steel plants and are more suitable for many developing countries where supplies of coking coal are limited.

The direct reduction process is intrinsically more energy efficient than the blast furnace because it operates at a lower temperature, and there are several other factors which make it economical. Iron metal and its oxides have melting points close to each other and these are more than 1500^0C. There are tendency for formation of formation of clusters , agglomerates and accretion or ring formation during actual manufacture of sponge iron in the temperature range of 900^0C to 1100^0C. Ring formation is a phenomenon occurring exclusively in a rotary kiln, while clusters and agglomerates are common in both rotary kiln and shaft based processes. In the presence of context we cannot conceive of a reactor to manufacture sponge iron, which operate above 1100^0C, even though there have been prolonged attempts to produce sponge iron and semi-fused iron at higher temperature. It is very easy to reduce the higher oxides of iron to FeO stage. It is only needed to meet the heat demand. The reductant and the temperature level. The reductant requirement and the temperature level. The key step in all DR processes is the reduction of FeO to metallic iron form. If an iron oxide pellet or lump is exposed to reducing gases like CO and H_2 at suitable temperature, it gives rise to sponge iron. In other way if we cover iron oxide lump with carbon or charcoal and heat in muffle furnace, it will give same result. Physical contact with carbon should cause reduction, but the interior of iron oxide lump or pellet also get reduced, which is not in contact with carbon. Further if we try to carry out the same exercise under progressively reduced pressures, the rate reduction progressively reduces. It is obvious, therefore, that reduction is effected by reducing gases, even if we keep iron oxide and coal in contact. For facilitating quicker regeneration of these reducing gases from coal an inclined rotary furnace is handy and convenient.

When an iron oxide pellet or lump or iron ore are charged into kiln along with coal, reduction occurs in layers. A pellet of satisfactory metallization would not have any core Fe_2O_3 left in it, while the parallel reduced layer would be restricted to very limited area in core.

Iron ore of high grade is available in Orissa / Jharkhand and availability is not a problem. Only the high cost of iron ore is causing a dent in the economics of scale of sponge iron industry. the market requirement and the huge production practice there is great scope of development in sponge iron making process. Computational fluid Dynamics is one of the emerging technology used for estimation of various process. In this project some sections of sponge iron making process were simulated. Some of the objectives of this project are

- Developing models for the equipment engaged with sponge iron making process with Computational fluid Dynamics package ANSYS 13.0.
- Developing a virtual process environment by fixing parameters similar to the industrial process.
- Comparing the simulated outcome with industrial values.
- Studding the behavior of process and its consequences towards changes in process parameter.
- Studding environmental effect of the process.

CHAPTER 02

LITERATURE REVIEW

In Sponge Iron industry Rotary kiln is the key equipment used to reduce iron ore to sponge iron form. For design and optimization of rotary kiln, it is necessary to understand the detailed processes that take place in the kiln. It is possible to get more insight, such as the distributions of gas-solid flow, temperature, and composition of gases and particles within a rotary kiln through mathematical modelling. However, only few expressions have existed so far for the processes in a cement rotary kiln to model the fuel combustion, heat transfer, and reduction chemistry. This is owing to the complexity of heat transfer that takes place simultaneously along with chemical and mineralogical reactions. Moreover, the onsite measurements for the detailed physical parameters are complicated and are not possible in many cases.

CFD modelling of such a system proves to be beneficial to understand the fluid flow, coal combustion and heat transfer phenomena in rotary kilns, and to improve the efficiency of these units. A steady-state heat transfer model for drying and preheating of wet solids with application to one reacting zone of a cement rotary kiln.[5] In the process conversion ratio of material is linearly dependent on the final temperature of reactor. For a good conversion ratio the temperature must be maintained between the minimum temperature and the limiting temperature.[6,7] CFD predictions for cement rotary kilns including flame modelling, heat transfer, and clinker chemistry were made by Mastorakos et al.,[8,9] in which a comprehensive model for most of the processes occurring in a sponge iron rotary kiln was presented. The results showed potential improvements in the models but only the temperature distribution was given, the gas composition distribution has not been predicted. A heat flux function to take into account the thermal effect of clinker formation. Combining the models of gas-solid flow, heat and mass transfer, and pulverized coal combustion, a set of mathematical models for a full-scale cement rotary kiln were established. In terms of CFD model, gas velocity, gas temperature, and gas components in a cement rotary kiln were obtained by numerical simulation.[10]

Rotary kilns are complex systems that involve occurrence of several simultaneous processes in both the bed and freeboard regions. It is thus essential to first identify key issues and use appropriate methodology to develop tractable computational models for rotary kilns. Key issues which need to be considered while developing a comprehensive model has been developed for cement kilns.[11]

Due to the complexity of the physics involved, and the occurrence of multiple phases with a large number of reactions in the bed/freeboard regions, very few CFD models have been published for rotary kilns. Most of these computational models do not account for the main key issues simultaneously in a single framework.[12] The bed and freeboard models were thus treated as separate domains, and coupling between them is handled explicitly. The geometry of the kiln was assumed to be axisymmetric in this work, and therefore, the boundary conditions were applied only in an approximate manner. Moreover, this work assumed a formation of coating throughout the kiln length. Karki et al . developed a 3D CFD-based model for simulating simultaneous combustion and heat transfer in cement kilns. [13] They have used an effective thermal conductivity to define degree of mixing in the bed region, developing a single computational model for simulating cement kilns. Different values of effective thermal conductivities at different locations in the kiln were used. However, there are no proper guidelines to choose proper effective thermal conductivity, and the values used are based on experience. It is also important to note that along with physical issues that need to be captured, there are numerical issues involved in cement kiln modelling. The freeboard region of the kiln in which combustion of coal takes place and the bed region of the kiln where reduction reactions take place are strongly coupled with each other. However, the characteristic time-and-space scales of the freeboard and bed regions are significantly different.[14]

CHAPTER 03

SPONGE IRON PROCESSING

Sponge iron production is being practiced from ancient time. Due to complexity in practice and lack of modern technology it was not so developed. Latter this was replaced by high productive modern Direct Reduction process in the mid of 19th century. Sponge iron is mainly produced from Iron ore in two methods

a. Using reducing gases like CO and H_2 in a shaft furnace.
b. Direct reduction by treating with coal as reductant.

In India companies adopt different technologies to reduce iron ore (Fe_2O_3) into sponge iron(Fe) form. Some most commonly practiced technologies are Midrex, HyL III, SL/RN, CODIR, Jindal, OSIL, SIIL, TISCO, Mini, Papuri Engg.

Being enriched with good quality Iron ore along with vast reserves of non-coking Coal, which likely last for another 200 years or so India is in an adventitious for coal based Sponge Iron plants. The total gross reserves of coking and non-coking coal in India are approximately 11,602 and 71,400 million tons respectively. From this prospective, the rotary kiln (coal based) DR process have developed well and vigorously in the country instead of natural gas based Shaft furnace or Retort furnace.

Due to its process advantages and product quality, SL/RN is mostly practiced. Some companies also adopt this after some modification. Use of Rotary Kiln as reactor makes it known as Rotary Kiln based Direct Reduction (RKDR). Strengths of Rotary Kiln produced Sponge Iron.

Govt. Of India concentrated on developing alternate technologies to produce iron with non-coking coal since 1970. Both NML and TATA STEEL have done basic groundwork in the sponge iron technology development and put up their pilot plant in 1972-1975. Subsequently UNIDO came forward in bringing SL/RN technology of sponge iron making to our country with LURGI GERMANY in 1979. A demonstration sponge iron plant of 30000 tpa(Tons per Annum) capacity was set up with liberal assistance from UNIDO, Govt. of India and LURGI. This humble beginning has grown tremendously to 22 million tons of installed capacity today. According to the adopted technologies coal fuelled kiln based process is mostly practiced by industries widely.

There are some key features which makes kiln based process different from other practiced sponge iron production.

- A sealed environment prevents external air to get into the system.
- Throwing or slinging of a coal stream into the kiln from the discharge end.
- Weight feeding along with proportioning of raw material.
- System of introducing controlled amount of air at regular intervals of length, which does not allow the product get oxidised in the bed.
- Facility of temperature measuring and recording at regular intervals.
- Treating waste gases and maintaining desired flow profile by pressure control method.
- In Kiln processing desulfurization is quite easy. For shaft process of sponge iron making prior & meticulous desulphurisation of natural gas is necessary to prevent poisoning of catalyst used of reforming.
- The solid charges get well mixed in rotary kiln get heated as well as reduced. This proper mixing helps in dilution of CO_2 formed around iron ore or sponge iron particle.
- A large free board (space above solid charge) gives it advantage to tolerate heavily dust-laden gases to avoid chocking of reactor, which is very essential for use of Indian high ash non-cocking coal.
- Rotary Kiln shows dual behaviour of coal gasifier as well as ore reducer. Preparation of reducing gases from coal is an expensive process which, is coming in the way of commercialisation of coal gasification based DR process. Therefore, Rotary Kiln process has proved commercially viable, even with low productivity per unit volume, because of its capability to perform two different functions simultaneously.
- In comparison to other technologies operating temperature is less in Kiln based process, leads to saving a great amount of energy.
- Kiln produced sponge iron particle have close granular size. So charging into electrical furnaces continuously and avoiding regular opening of roof. Continuous charging permits partial refining during melting stage as the particle passes through the slag layer into the mixed layer. If adequate heat is available, operation time as well as refining time get reduced.

Raw Materials; Iron ore or pellets, reductant natural gas or on-coking coal and limestone/dolomite are the main raw materials. The quality requirements of the raw materials in general are

Iron Ore : Iron ores are naturally found mineral rocks from which metallic iron can be economically extracted. The ores are usually rich in iron oxides and vary in colour from dark grey, bright yellow, deep purple, to rusty red. The iron itself is usually found in the form of *Magnetite* (Fe_3O_4), *Hematite* (Fe_2O_3), *Goethite* (FeO(OH)), *Limonite* (FeO(OH).n(H_2O)) or *Siderite* ($FeCO_3$). Ores carrying very high quantities of hematite or magnetite (greater than ~60% iron) are known as "Natural Ore" or "Direct Shipping Ore". Lumps or pellets with high iron content, low gangue content, good mechanical strength, readily reducible and with size ranges from 4 to 20 mm in diameter.

Natural Gas or Non-coking Coal : These are the reductants in the process. The characteristic desired for non-coking coal are that the non-coking coals should have high fixed carbon content and high volatiles content. Ash, sulphur and moisture in coal should be low. The ash fusion point of coal is required to be high. The coal should be highly reactive and should have low coking and swelling indices. Though coal is administered into kiln at both inlet and outlet end for two different purposes.

a. Feed Coal enters into kiln at upper end along with iron ore. Having size of 4 to 20 mm. in diameter.
b. Injection coal or Sling coal which, is injected into the kiln at discharge end. Sling coal caries mixture of coarse coal 0.4 to 20 mm whereas Fine coals of size less than 0.4 mm. Variation in coal particle size help in well distribution of coals throughout the freeboard. Sling coal is essential for creation of reducing environment in the free board of kiln.

Dolomite: Dolomite is a double carbonate, having a different structural arrangement. It is a carbonate mineral composed of calcium magnesium carbonate $CaMg(CO_3)_2$. These should have lime and magnesia content of 45% or above. The grain size of raw materials is also important (2 to 6 mm in diameter) factor in direct reduction process. It is used as a desulphurizing agent. The Ca and Mg ions play a major role in removal of sulphur from the process.

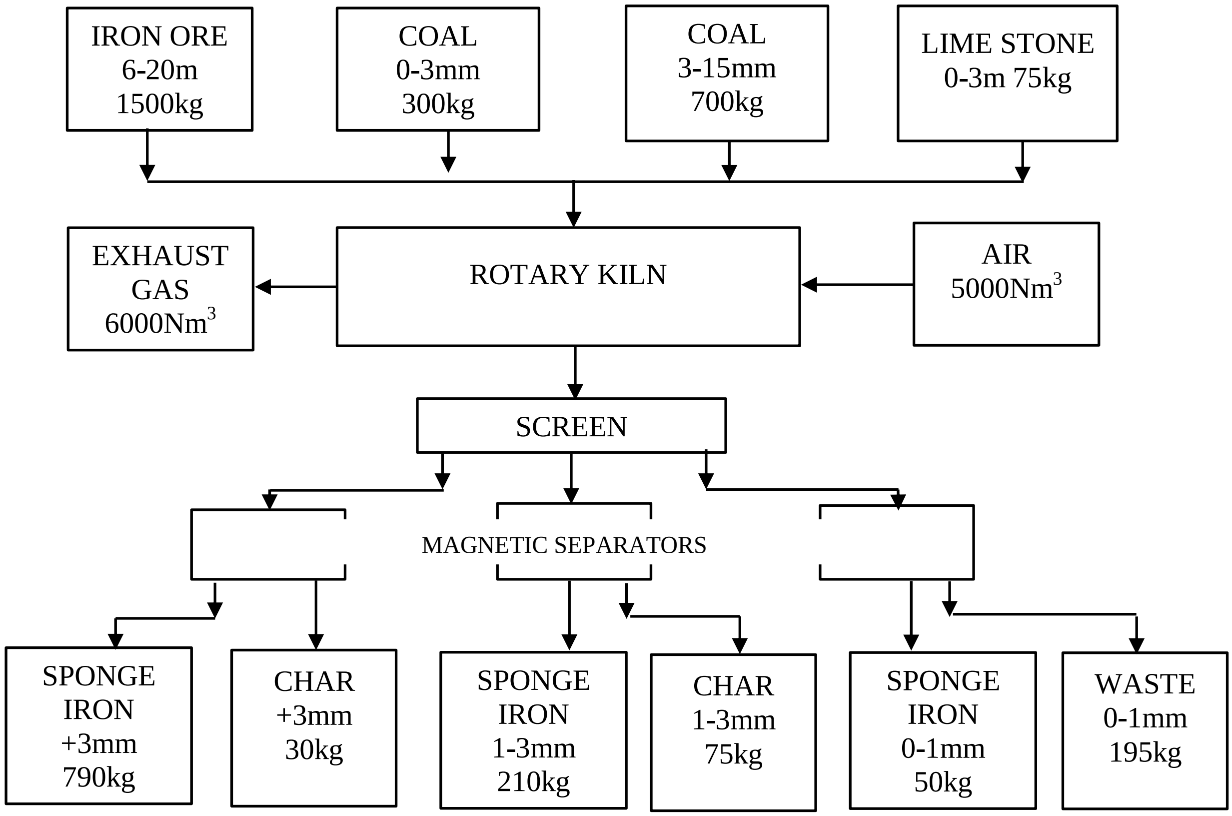

Fig: 3.1. Material Balance in a Rotary Kiln sponge iron plant[15].

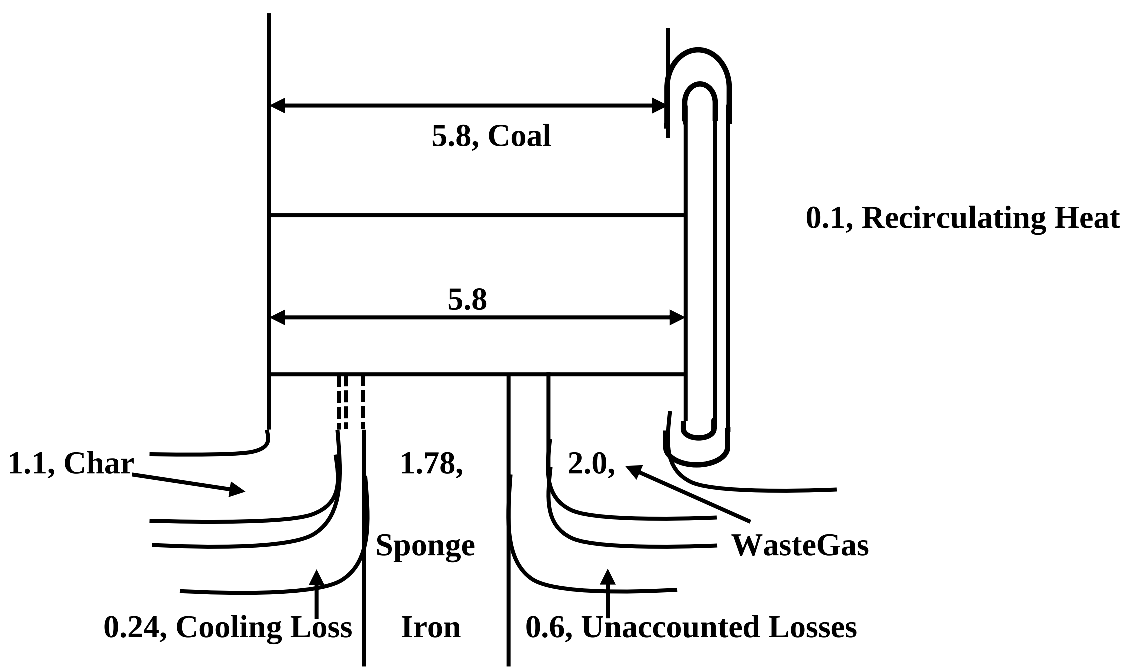

Fig: 3.2. Energy Balance in a Rotary Kiln sponge based iron making [15]

3.1. **Process Principle**

The process of Sponge Iron making in Rotary Kiln is dependent on certain principles.

- Thermodynamics and kinetics of Gasification and reduction reaction.
- Temperature profile and Heat transfer from free board to bed region of kiln.
- Fluid Dynamic behaviour and flow profile of air inside of Kiln.
- Flow, mixing and residential time of solid material inside Kiln.
- Reducibility of Iron ore and reactivity of coal, so that we can fix the grade of raw material and its proportion.
- Generation and retention of reducing environment in the free board region.

The overall reduction process is highly energy demanding because all reaction are endothermic reactions. So additional energy need to be supplied by burning coal or any other fuel sources. Thermodynamic studies of important reactions involved in sponge iron process are given in following table.

Table 3. 1.: Thermodynamic data of important reactions.[16], *ΔG* & *ΔT* in *kCal/Kg.*mole, *T* in ^{o}K

Si. No.	Reaction	ΔG^0_T	ΔG^0_{298}	ΔG^0_{1273}	ΔH^0_{298}	ΔH^0_{1273}
1	$Fe_2O_3 + CO \rightarrow 2\ FeO + CO_2$	+2,120 – 10.39T	-976	-11,106	+2,270	-2,532
2	$FeO + CO \rightarrow Fe + CO_2$	-4,190 +5.13T	-2,661	+2,340	-4,430	-5,808
3	$C + CO_2 \rightarrow 2CO$	-94,200 - 0.2T	-94,260	-94,455	-94,050	-94,561
4	2CO + O2 $\rightarrow$ 2CO2	+40,800-41.70T	+28,373	-12,284	+41,210	+39,964
5	FeO +C $\rightarrow$ Fe + CO	+36,610-36.57T	+25,712	-9,944	+36,780	+34,277
6	$Fe_2O_3 + 3/2\ C \rightarrow 2Fe + 3/2CO_2$	54,940-62.68T	+36,261	-24,852	+55,225	+50,573

.

Reaction 1 & 2 are **Reduction reactions**. Earlier one is feasible so, it is easy to be started in the reduction zone of kiln. But the second one is the key step in this reduction process. Under standard kiln condition (nearly at 1000^{o}C) conversion of FeO to Fe is not feasible. But in presence of CO reaction becomes quite easier at this temperature. Therefore we have to maintain CO/CO_2 ratio at a specific value *i.e.* 2.52. The concentration of CO_2 in the vicinity of iron ore particles is not allowed to build up above 28%. This can be achieved by a faster gasification reaction.

Reaction 3 & 4 are **Gasification Reactions**. Reaction 4 is an essential step in gasification. It can occur at Kiln operating temperature. The rate of gasification is certainly dependent on the nature of surface of char and the coal used. Coal which yields reactive char can quickly convert CO_2 to CO which, is quite essential to make the reaction move forward.

Reaction 5 & 6 are representation of overall reactions happening in a kiln based sponge iron making. Reaction 5 representation of Overall reactions occurring in reduction zone. Reaction 6 representation of Overall reactions for the RKDR process. These are highly endothermic heat required reactions. The energy demand for these endothermic reactions is satisfied by burning of additional coal.

There are some key feature points considered during sponge iron process development and are responsible for the kinetics of the process.

3.1.1. Reaction Kinetics: There are many hindrance to various steps in process like, high activation energy, long diffusion paths, low porosity and some physical barriers. The molecularity of most of reactions is two or more. But the overall reaction is a first order reaction which, implies that convenient intermediate formation in reduction processs.

3.1.2. Iron ore reducibility: reducibility is the ease of removal of oxygen combined with iron molecule in oxide form. The reaction is a gas-solid interaction process, reduction in the interior of lumps and pellets should have been difficult., had it not been accompanied by a large volume reduction. The resulting pores which form on the surface allows gases to access the lump or pellet to make the reduction commercially viable. As hematite ores can be reduced upto 33% without effecting any metallisation, measuring reduction rates up to 33% reduction region would not serve any purpose as the key step in in the process is the reduction of FeO to Fe. High grade hematite ores have adequate reducibility for sponge iron making. Presence of gangue reduces the reductability.

3.1.3. Coal Char reactivity: Another parameter used to fix the raw material estimation. It is the ease of reaction of carbon with carbon dioxide to generate carbon monoxide. In other way known as *Carboxy Reactivity*. This is measured by reacting the char with carbon dioxide at 950 to 1000^{o}C and measuring the extent of conversion to carbon monoxide and it determined as the volume of carbon monoxide formed per second per gram of char sample. Chars exposed to high temperature lose their reactivity gradually with time. Therefor preheated chars or returned chars are very poor in reactivity.

3.1.4. Iron Ore-Coal compatibility: Iron Ore-Coal compatibility test determines the combination and proportion and behaviour of coal-ore mixture. This test is carried out under conditions similar to industrial kiln environment. The overall metallization (Fe(M)/ Fe(T)) of the magnetic fraction should be above 90% for the combination to commercially viable.

3.1.5. Re-oxidation characteristics of sponge iron: Sponge irons are highly porous in nature(can rise up to 54%. These pores increases surface area, exposed to the atmospheric air for oxidation and the sponge iron has to be cooled out of contact from any air, oxygen, moisture or even carbon dioxide.

3.1.6. Crossing Point Temperature(CTP): It is the determination of propensity of oxidation in presence of air. In this technique a beaker full of sponge iron kept in muffle furnace. As slowly the furnace temperature rises, the temperature of sponge iron at centre of beaker rises slowly. It is commonly observed, the sponge iron temperature lags the furnace temperature. But at a certain point Sponge iron at centre of beaker exceeds furnace temperature. This point is known as Crossing Point Temperature. CPT for Sponge iron lies between 200 to 350^{o}C. Lower the CTP easier for sponge iron to keep the temperature.

3.1.7. Heat Transfer in Rotary Kiln: Heat transfer in rotary kiln takes place by conduction, convection & radiation. The conversion of FeO to Fe is endothermic. Heat form freeboard gases get transferred to the bed region to maintain the bed temperature. This heat loss from freeboard is made up by combustion of CO to CO_2. The total heat transfer phenomenon in rotary kiln is represented by nine mathematical equations.

$H_1=A_1(T_g - T_b)$	H_1 = Conductive & convective heat transfer from gas to charge board	(3.1)
$H_2=A_2(T_g^4 - T_b^4)$	H_2 = Radiative heat transfer from gas to charge board.	(3.2)
$H_3=A_3(T_g - T_r)$	H_3 = Conductive & convective heat transfer from gas to refractory.	(3.3)
$H_4=A_4(T_g^4 - T_r^4)$	H_4 = Radiative heat transfer from gas to refractory	(3.4)
$H_5=A_5(T_r - T_b)$	H_5 = Conductive & convective heat transfer from refractory to charge board	(3.5)
$H_6=A_6(T_r^4 - T_b^4)$	H_6 = Radiative heat transfer from refractory to charge bed.	(3.6)
$H_7=A_7(T_r - T_s)$	H_7 = Conductive heat transfer through refractory lining of rotary kiln.	(3.7)
$H_8=A_8(T_s - T_a)$	H_8 = Conductive heat transfer from kiln surface to atmosphere.	(3.8)
$H_9=A_9(T_s^4 - T_a^4)$	H_9 = Radiative heat transfer from kiln surface to atmosphere.	(3.9)

Where g → Gas
b → Charge bed
r → Refractory surface
s → Kiln Surface.
a → Atmosphere or surroundings

3.1.8. Gas evolution and Flow rate: The entire gas coming out of kiln is generated within the kiln itself. There is a net outflow of CO rich gas from charged bed to the free board. Towards the solid discharge end, when reduction is almost complete gas evolution is minimum and just for a small fraction of the total length the gas flow in the freeboard is lamellar or mixed region. In rest of the kiln, Reynolds number calculation indicated a fully turbulent flow throughout. The linear gas velocity in a typical upto 30m/s have apparently been used in these kiln without hindering the forward movement of the granular bed material.

3.2. <u>Coal Requirement Calculation</u>

Estimation of the required amount of coal for Rotary Kiln Direct reduction process. During calculating it is an overall assumption that, "Radiation Loss and Unaccounted has been taken to be 0.6Gcal/t sponge iron". Waste gases are assumed to be completely combusted *i.e.* no volatile matter is allowed to go out free or partially reacted. There are four variants taken into consideration

i. Conventional process, waste gas going out at 1200^{o}C.
ii. Conventional process, waste gas going out at 1000^{o}C.
iii. Conventional process, waste gas going out at 800^{o}C.
iv. Process with Pre-heating of iron ore, char and flux to approx. 700^{o}C and air preheating to an average temperature of 400^{o}C.

In variant I, ii and iii the system has been considered up to a point where the combustibles in the waste gases have been fully burnt with stoichiometric amount of air. Rapid transfer of heat starts before completion of combustion. As a result the temperatures in actual ABC's are much lower than what is indicated.in variant (iv), inputs have been taken from a heat transfer calculation carried ut based on model developed and tested in the pilot rotary kiln, operating the kiln as though it was a preheating kiln only. For a 500tpd sponge iron production a 3.0m dia and 30m long preheating kiln is required. The temperature of charge is 664^{o}C and waste gas is 700^{o}C. Without any drying of charge, reduction of iron ore or calcination of flux takes place in preheating kiln. If a partial reduction or calcination takes place, heat transfer would be further enhanced and energy saving would be still better.

The ultimate analysis shows the coal composition Moisture (8.5%), Ash (24.1%), Carbon(55.3%), Hydrogen(3.2%), Sulphur(0.6%), Nitrogen(1.4%), CO_2 as carbonate(0.5%), Oxygen(6.4%). Whereas proximate analysis gives Fixed carbon (41.7%) and volatile material (27.8%). For 95% of Fe_2O_3 conversion amount of coal required is nearly 85 % of total Iron ore is go to be reduced.

3.3. <u>Process</u>

Gas sealing in kiln prevents external air to ingress into the system, which makes RK-DR process of sponge iron making successful. The draught control and maintaining slightly positive pressure in the reactor mechanical seals were used. There are certain design features adapted in RK-DK process for a better reduction process and making it energy efficient.

3.3.1. Air Tube: Controlled oxidation of CO in freeboard takes a vital position for maintaining a constant temperature profile over the entire reduction zone of the kiln. In SL/RN process practice this requirement is met by inserting temperature resistant metallic **air tubes**. Shell mounted fans blow air into these air tubes along the axis of kiln, so that the air does not oxidise the reduced iron in the charge bed.

3.2.2. Slinging of Coal: Toward the discharge end of kiln, where FeO is being reduced to metallic iron, the char in the bed does not remain reactive. But in this part of kiln more reactive char is needed since the final stage of reduction are most critical one. Fine coals along with coarse coal were thrown or sling into kiln at discharge end. This throwing or slinging is done with air medium. This transportation or throwing is achieve in Dilute phase *i.e.* the quantity of air used for transportation is a small fraction of what is needed for complete combustion of coal. Fine coal particles cannot gather enough momentum to reach desired length of kiln; it is the current of freeboard gas moving towards the charging end which shoulders the fine particles to reach appreciable distances. The coarse coal particles can gather sufficient momentum to reach larger distances. For this the particle should be given sufficient time and distance to attain full momentum before being released into the kiln environment. Therefore coals carried in along straight pipe of length of 35 metre or more than that. In this way nearly 40% of total cola used is feed into kiln at the discharge end. More the coal percentage of coal we use at discharge end, process is more energy efficient the process would be as the volatile mater in coal would be utilised within the kiln itself. But slinging more cola into kiln means blowing more carrier air into kiln. Excess entry of air into kiln disturbs the balance maintained between oxidising and reducing layers in the rotary kiln. This not only oxidise the reduced sponge iron, it may rise temperature of inside kiln and chance of accretion formation.

3.2.3. Waste Heat Recovery System: A large part of energy from coal fuel comes out with waste gas. This energy is utilized as source of sensible heat for electrical power generation. The amount of energy generated used for internal requirements. Companies like JSPL and M/s HEG Ltd. sale the surplus amount energy to state electric board.

3.2.4. Use of Waste gas energy for preheating: Along with power generation, waste gas can be utilized to return energy back into system. The off gas can be used for drying of raw materials can bring a significant change in energy efficiency. For a reduction kiln the filling degree must be much lower. Practice has shown that 15% filling degree impairs the process of reduction, because for reduction purpose a large freeboard is needed to maintain the balance between oxidising and reducing zone. Both functions of reduction and preheating were separated in two different kilns. The preheating kiln, where large volume reduction of gas is expected due to temperature drop, may take a conical shape for greater effectiveness.

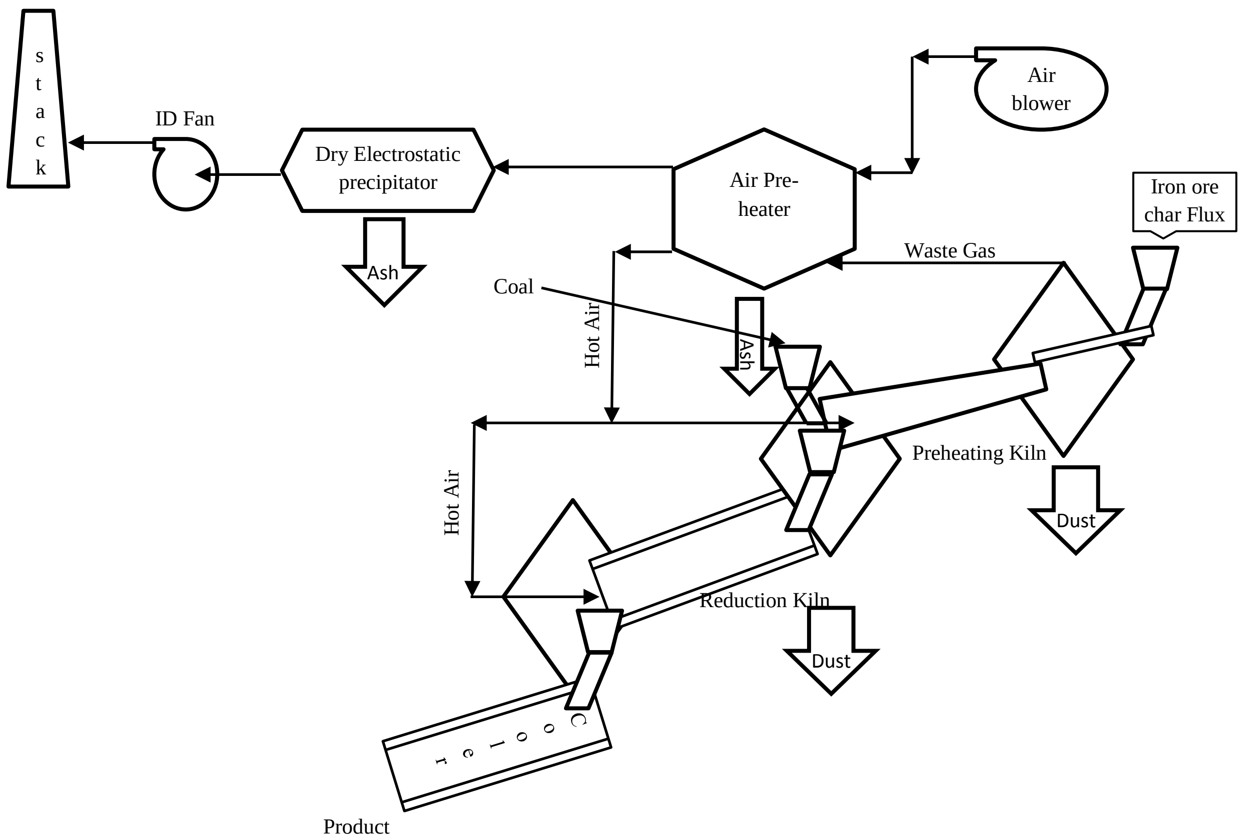

Fig:3.3.: Schematic of optimised Rotary kiln sponge iron making process.

Iron Ore and Non Coking Coal along with Dolomite are fed continuously to the charge end of Rotary Kiln which is inclined at 2.5% of drum length. Coal is also injected through a Coal Throw Pipe at the discharge end of Kiln. Due to the inclination and rotation of Kiln the charge material moves along the length of Kiln and it is discharged continuously after processing. To supply heat for the process air is blown into the Kiln through central burner and air pipes mounted on the Kiln shell. As the charge moves along the kiln, it is heated by the gases which flow in opposite direction. The first section, approximately half of kiln is called preheating zone where iron ore, coal and dolomite are dried and heated to reaction temperatures using the heat released from the combustion of volatile matter and carbon in the coal . The second half of kiln is called reduction zone where major amount of Oxygen contained in the iron ore is removed leaving metallic iron (Fe). De-sulphurisation in the Rotary Kiln is effected by calcined limestone/dolomite. The chemical reactions taking place at various zones in the rotary kiln are as given in table 3.1.

The reduced iron ore -SPONGE IRON with unburnt char from rotary kiln gets discharged into a Rotary Cooler. The heat will be dissipated indirectly by water spraying into the outside of Cooler Shell. The material gets cooled to around 1200^0C.

CHAPTER 04

ROTARY KILN DESIGN & OPERATION

Rotary Kiln, a cylindrical vessel, inclined slightly to the horizontal as in Fig. 4.1, which is rotated slowly about its axis. The material to be processed is fed into the upper end of the cylinder. As the kiln rotates, material gradually moves down towards the lower end, and may undergo a certain amount of stirring and mixing. Hot gases pass along the kiln, sometimes in the same direction as the process material (co-current), but usually in the opposite direction (counter-current). The hot gases may be generated in an external furnace, or may be generated by a flame inside the kiln. Such a flame is projected from a burner-pipe (or "firing pipe") which acts like a large Bunsen burner.

Fig.4.1. Industrial view of Sponge Iron making Rotary Kiln[17].

4.1. Kiln & its specifications

A typical 500TPD capacity plant Kiln is **80 m in length** and having **4.34 m inner** & **4.85 outer diameter**. The basic components of a rotary kiln are the shell, the refractory lining, support tyres and rollers, drive gear and internal heat exchangers. There are some important components of Rotary kiln.

4.1.1. Kiln Shell: This is made from rolled mild steel plate, usually between 15 and 30 mm thick, welded to form a cylinder. This will be usually situated on a east/west axis to prevent eddy currents. Upper limits on diameter are set by the tendency of the shell to deform under its own weight to an oval cross section, with consequent flexure during rotation. Length is not necessarily limited, but it becomes difficult to cope with changes in length on heating and cooling (typically around 0.1 to 0.5% of the length) if the kiln is very long.

4.1.2. Refractory Lining: The purpose of the refractory lining is to insulate the steel shell from the high temperatures inside the kiln, and to protect it from the corrosive properties of the process material. It may consist of refractory bricks or cast refractory concrete. The refractory selected depends upon the temperature inside the kiln and the chemical nature of the material being processed. Normally Andalusite based fire bricks with low thermal conductivity (1.0 W/mK) and high cold crushing strength(100 N/mm^2) are preferred. Dense fiber Aluminum-silicate refractories in the range of 45-85% alumina should meet the requirement. Silica wool or similar insulating blanket of 25 to 50 mmm thickness is thereafter laid out against the shell followed by 50 to 75 mm layer of insulating blocks. Finally 125 to 150 mm layer of castable are laid out. A typical refractory will be capable of maintaining a temperature drop of 1000°C or more between its hot and cold faces. The shell temperature needs to be maintained below around 350°C in order to protect the steel from damage, and continuous infrared scanners are used to give early warning of "**hot-spots**" indicative of refractory failure.

4.1.3. Tyres and Rollers: Tyres, sometimes called riding rings, usually consist of a single annular steel casting, machined to a smooth cylindrical surface, which attach loosely to the kiln shell through a variety of "chair" arrangements. These require some ingenuity of design, since the tyre must fit the shell snugly, but also allow thermal movement. The tyre rides on pairs of steel rollers, also machined to a smooth cylindrical surface, and set about half a kiln-diameter apart. The rollers must support the kiln, and allow rotation that is as nearly frictionless as possible. A well-engineered kiln, when the power is cut off, will swing pendulum-like many times before coming to rest. The longest kilns may have 8 sets of rollers, while very short kilns may have only two. Kilns of Sponge Iron Industry usually rotate at 0.35 to 0.7 rpm. The bearings of the rollers must be capable of withstanding the large static and live loads involved, and must be carefully protected from the heat of the kiln and the ingress of dust. In addition to support rollers, there are usually upper and lower "retaining (or thrust) rollers" bearing against the side of tyres, that prevent the kiln from slipping off the support rollers..

4.1.4. Drive Gear: The kiln is usually turned by means of a single Girth Gear surrounding a cooler part of the kiln tube, but sometimes it is turned by driven rollers. The gear is connected through a gear train to a variable-speed electric motor. This must have high starting torque in order to start the kiln with a large eccentric load. Temperature differences between the top and bottom of the kiln may cause the kiln to warp, and refractory is damaged. It is therefore normal to provide an auxiliary drive for use during power cuts. This may be a small electric motor with an independent power supply, or a diesel engine. This turns the kiln very slowly, but enough to prevent damage.

The firing mechanism of Rotary Kiln has four basic components.

4.1.5. Internal heat exchangers: Heat exchange in a rotary kiln may be by conduction, convection and radiation, in descending order of efficiency. In low-temperature processes, and in the cooler parts of long kilns lacking preheaters, the kiln is often furnished with internal heat exchangers to encourage direct heat exchange between the gas and the feed as in fig.4.2 . These may consist of scoops or "lifters" that cascade the feed through the gas stream, or may be metallic inserts that heat up in the upper part of the kiln, and impart the heat to the feed as they dip below the feed surface as the kiln rotates. The latter are favored where lifters would cause excessive dust pick-up. The most common heat exchanger consists of chains hanging in curtains across the gas stream. The thermal efficiency of the rotary kiln is about 50-65%.[18]

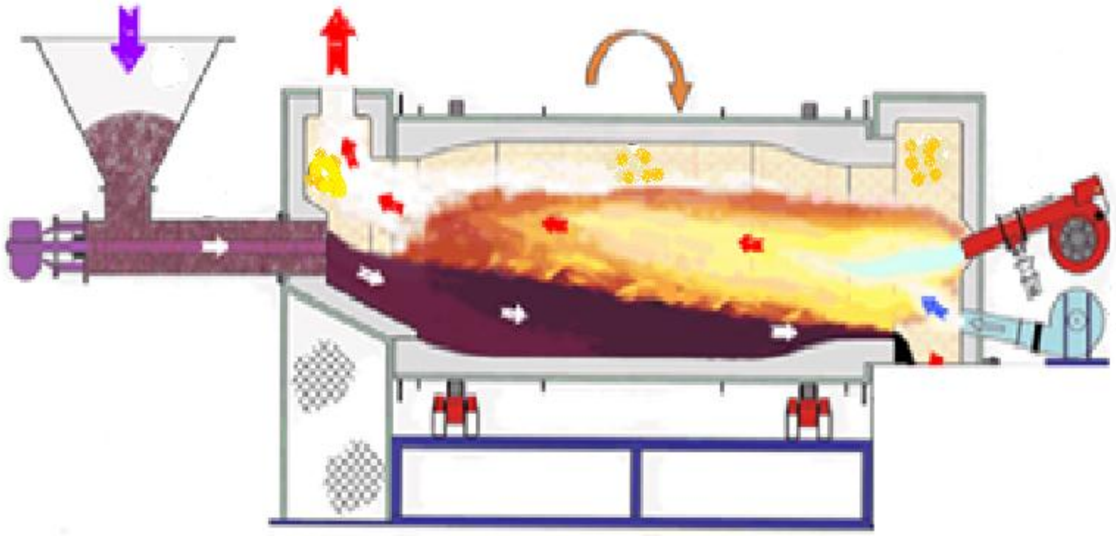

Fig. 4.2: Schematic view of internal heat exchange in Rotary kiln.

4.1.6. Rotary air lock feeder: Rotary air lock feeder provides positive seal to the injection air as well as medium for injecting coal. In order to ensure proper sealing of blown air, it is essential to maintain clearance between the rotary blade tips and casing within 0.25 to 0.5 mm. The compressor attached to it blows air at rate of 1300 to 1600 cubic meter/hour.

4.1.7. Lobe Blower: Lobe blower is attached to a compressor designed for free air delivery of 12000 to 15000 cubic meter/hour at 1.0 bar pressure for 500 TPD kiln. The air is divided in two channels. One is high volume main axial air and another is a swirling radial air. At the center of Lobe blower a diesel throwing jet is present as schematically represented in Fig.4.3. This injected diesel is fired externally. Lobe blower is the start-up source of heat for the kiln.

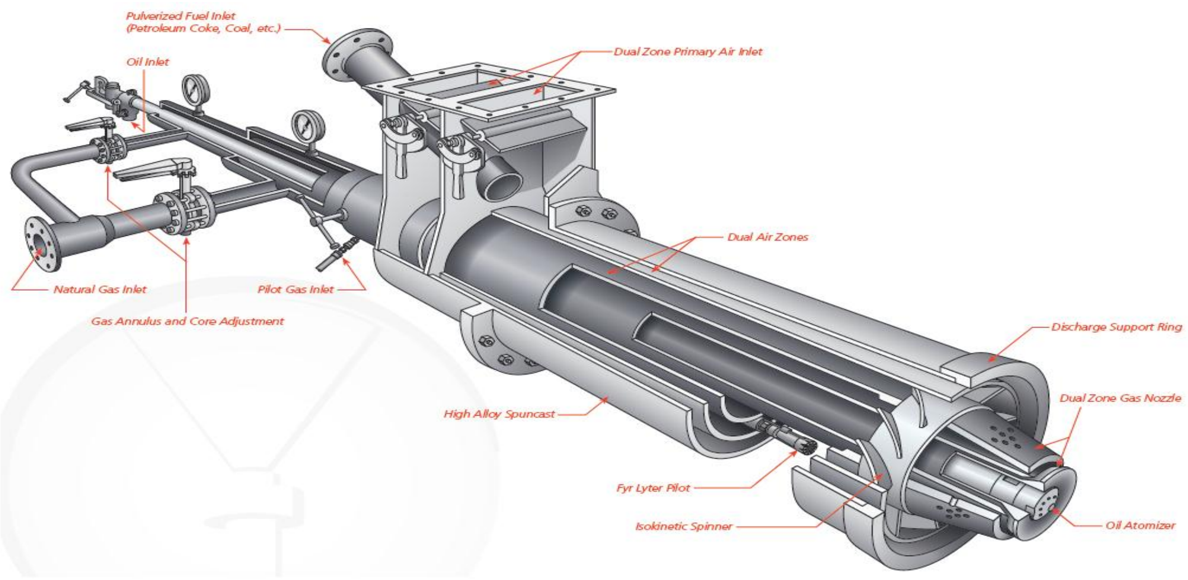

Fig. 4.3: Schematic view of Lobe Blower.

4.1.8. Coal Throw Pipe: Coal has to be distributed in the entire reduction zone kiln depending upon heat demand in every zone. In order to ensure effective coal injection, we need the mixture of fine coal 0-0.5mm and coarse coal 4 mm – 20 mm. Generally 0 to 1 mm coal travels a distance of 5 meters and 2 to 4 mm travels a distance 16 meter, 4 to 6mm travels distance of 20 meters and 6 to 8 mm travels at a distance of 22 meters and +8mm travels distance 26 meters. As per this analysis we need the coal all the size fraction for proper distribution in the kiln as per requirement. It throws nearly 1500 tons of coal per hour.

4.1.9. Ari Tubes: These are external compressor attached tubes enters into kiln drum to blow air in a counter stream to flow in bed. There are nine air tubes installed across the length of kiln. Air tubes are separated at distances of 8.1, 8.1, 5.7, 6.7, 6.7, 6.7, 6.7 & 4.6m. respectively. Air flow rate in these tubes 10000 cubic meter/hour.

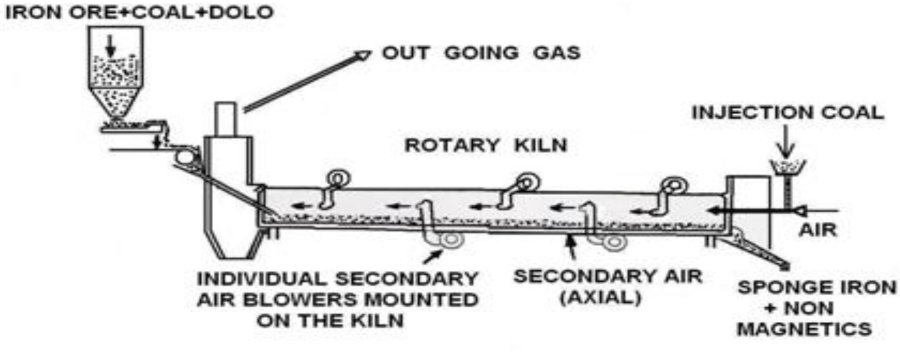

Fig. 4.4: Schematic view of Air & material flow in Rotary kiln.

4.2. Bed Phenomenon

During the thermal processing of granular materials in rotary kiln, heat transfer within the bed material occurs by the same mechanisms as in any packed bed. Heat transfer paths at play can be particle-to-particle conduction and radiation, as well as interstitial gas-to-particle convection. The movement of particle themselves superimpose an advective component for energy transport. There are two dispersion mechanisms, one is axial direction that is characterized an axial mixing coefficient, and the other in transverse direction, which is associated with radial mixing coefficient. The axial flow of bed in kiln depends upon the rotation rate, degree of fill and rheological properties of material. Though the vessel is partially filled and rotating on its horizontal axis, the freeboard depends on kiln loading or percentage of filling. The key geometrical feature is the vessel size, given in term of cylinder diameter and Length related by the aspect ratio, *i.e.* the Length to Diameter ratio (*L/D*) and also the slope of kiln inclination. Movement in the axial direction determines residence time and transverse affects process phenomena like mixing, heat transfer and reaction rate.

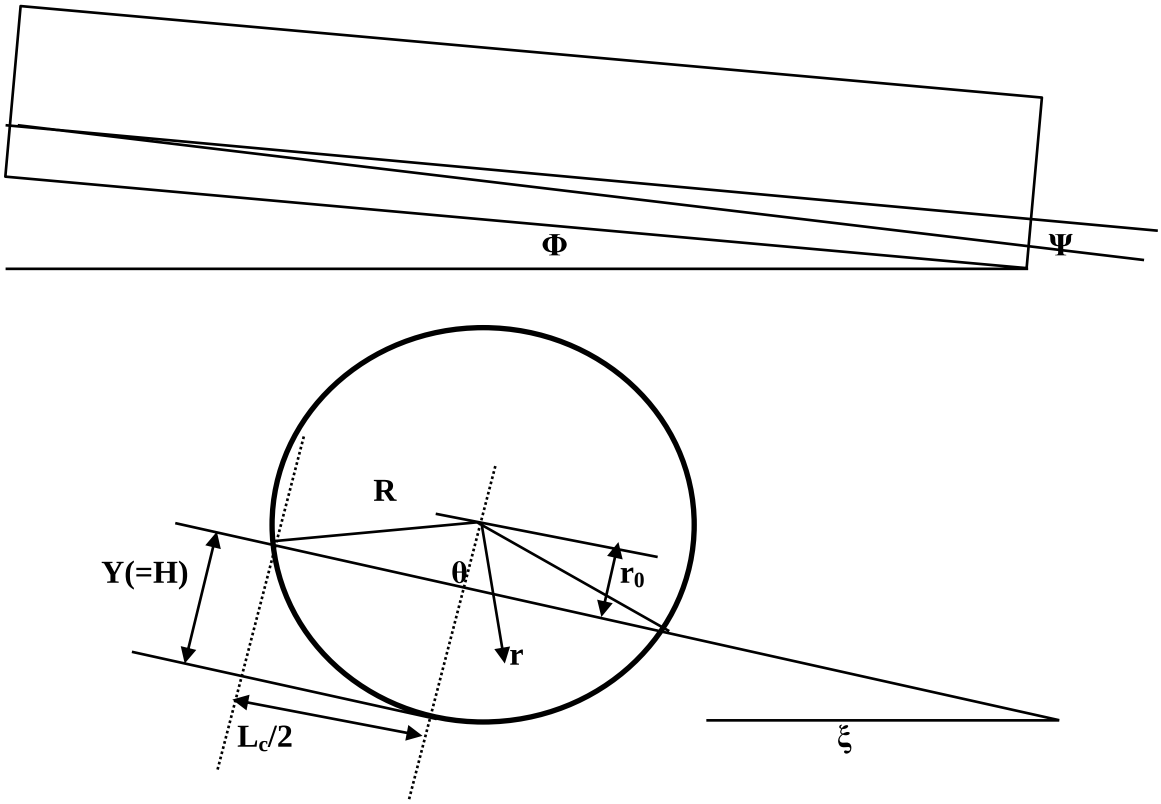

Fig. 4.5:Filling of Bed Geometry

The fraction filled defining the bed depth, and based on the geometry, relates the angels at any transvers section shown in fig.4.5.

$$f_c = \frac{1}{2\pi}\left(2\cos^{-1}\left(\frac{R}{R-H}\right) - \sin\left[2\cos^{-1}\left(\frac{R}{R-H}\right)\right]\right)$$

A heap of granular material and distributed by vibrating the base, the material flows in both direction. If the base is inclined the material will flow downward. This material flow in inclination of Rotary kiln even without the geometrical effect of rotation and just by providing disturbance to bed. Movement of charge material from the upper to lower end of kiln due to two factors. One is forward movement can be calculated by geometry of cascading and second one is additional forward movement due to constant disturbance of bed. Axial motion of a particle at any point of distance **r** axis with **n** kiln rotation speed is[19]

$$u_{ax}(r) = nL_c\left(\frac{\boldsymbol{\Phi} + \boldsymbol{\psi}\cos\boldsymbol{\xi}}{sin\boldsymbol{\theta}}\right)\left(\frac{\pi}{\sin^{-1}\frac{L_c}{2r}}\right)$$

Using the same geometrical considerations by Seaman, dimensionless residence time and flow rate may be derived [20] as function of f(y/R). Using L_c =y(2R-y) and sinθ = L_c/R, the dimensionless residence time can be expressed as

$$\overline{\tau_d} = \frac{\bar{\tau}nD\tan\emptyset}{L\sin\boldsymbol{\xi}} = \frac{\sin^{-1}[(2-y/R)y/R]^{1/2}}{\pi[(2-y/R)y/R]^{1/2}} = f(y/R)$$

4.3. <u>Freeboard Aerodynamic Phenomenon</u>

The fluids flows in Rotary Kiln are the primary air, secondary air, combustion products and infiltration air. usually the combustion system is such that the primary air issues from burner nozzle as a jet into an open tube or into a tube surrounded with secondary air prior to combustion. The use of swirling jet has long been one of the partial way of inducing mixing and improving burner effectiveness in rotary kilns. The increased flame stability and intensity associated with swirling are due to improved recirculation vortex which, like high velocity primary air jets returning hotter combustion gases to the flame front where they become entrained in the primary air fluid prior to ignition and this enables the transfer of energy to incoming reactants. Swirl burners typically seek to stabilize the flame by creating central recirculation zone and an external recirculation zone. Pulverized coal combustion swirl jets improves particle residence time in the combustion zone, and consequently improves combustion efficiency. Increasing the swirl number and thereby the jet angel moves the external recirculation eddy closer to the burner.

The Kiln aerodynamics has an important effect on dust carryover from kiln processing material. The phenomenon of dust pick up by air known as saltation. If the particle is heavy and air velocity is very high, the gas flow over bed surface is will induce motion known as saltation, in which individual grain get ejected from the surface by following distinctive trajectories under the influence of gas velocity, resistance and gravity.

4.4. Mixing and Segregation of granules in Bed.

The governing equations for mixing and segregation were derived by considering equilibrium balance of material for control volume.[21]These equations are

For Bulk Flow

$$Au(y)C_j = Au(y)\left[C_{j_{/x}} + \frac{\partial}{\partial x}(C_j)dx + \frac{\partial^2}{\partial x^2}(C_j)dx^2 + \cdots\right]$$

For diffusion

$$-\bar{r}\frac{\partial C_j}{\partial y_{/_{y-dy,x}}} = -\bar{r}\left[\frac{\partial C_j}{\partial y_{/_{y,x}}} - \frac{\partial}{\partial y}\left(\frac{\partial C_j}{\partial y}\right)dx + \cdots\right]$$

For Segregation

$$\bar{k}\, C_{j_{/_{y+dy,x}}}\left[1 - C_{j_{/_{y,x}}}\right] = \bar{k}\left[1 - C_{j_{/_{y,x}}}\right]\left[C_{j_{/_{y,x}}} + \frac{\partial}{\partial y}(C_j)dy + \cdots\right]$$

$$\bar{k}\, C_{j_{/_{y,x}}}\left[1 - C_{j_{/_{y-dy,x}}}\right] = \bar{k}\, C_{j_{/_{y,x}}}\left[1 - \left\{C_{j_{/_{y,x}}} - \frac{\partial}{\partial y}(C_j)dy + \cdots\right\}\right]$$

CHAPTER 05

COMPUTATIONAL FLUID DYNAMICS (CFD) & ITS APPLICATION

Computational fluid dynamics (CFD) is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyses problems. Computational fluid dynamics (CFD) is concerned with numerical solution of differential equations governing transport of mass, momentum, and energy in moving fluids. Computational fluid dynamics is a virtual prototype that guides in building accurate flow models by solving transport equations. The feature of combustion flows can be analyzed in detail with Computational fluid dynamics. Design (From the concern of sizing, economic operation, and safety) of engineering equipment such as heat exchangers, furnaces, cooling towers, internal combustion engines, gas turbine engines, hydraulic pumps and turbines, aircraft bodies, sea-going vessels, and rockets depended on painstakingly generated empirical information.

In particular mixing, temperature, flow velocity, flame stability and concentration of combustion species can accurately be computed in different geometry. The general gas flow pattern, pressure field, velocity vector and reactant species concentration can be mapped in a three dimension manner. So it is easier for us to determine the mixing, recirculation and reactive zone inside of kiln. The physical and chemical phenomenon of reacting flow may be simulate by numerical solvers, a set of generalized conservation equations for flow(Navier Stokes equations) associated with a set of equations for enthalpy, combustion and so on. It therefore makes it possible to evaluate useful operational parameters of interest for design optimization prior to prototyping or trouble shooting an existing design for operation. There are three basic governing transport laws give rise to some fundamental equations. All process simulations were done by developing mathematical models form these governing equations. The three basic governing transport laws are the following:

1. The law of conservation of mass (transport of mass),

2. Newton’s second law of motion (transport of momentum), and

3. The first law of thermodynamics. (transport of energy).

The governing equations are

The conservation of mass equation for the mixture

$$\frac{\partial \rho_m}{\partial t} + \frac{\partial (\rho_m u_j)}{\partial t} = 0$$

Equation of Mass Transfer for Species k

$$\frac{\partial(\rho_m \omega_k)}{\partial t} + \frac{\partial(\rho_m u_j \omega_k)}{\partial t} = \frac{\partial}{\partial x_j}\left[\rho_m D_{eff} \frac{\partial \omega_k}{\partial x_j}\right] + R_k$$

Momentum Equations u_i (i = 1, 2, 3)

$$\frac{\partial(\rho_m u_i)}{\partial x_j} + \frac{\partial(\rho_m u_i u_j)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\mu_{eff} \frac{\partial u_i}{\partial x_j}\right] - \frac{\partial p}{\partial x_j} + \rho_m B_i + S_{u_i}$$

Energy Equation – Enthalpy Form

$$\frac{\partial(\rho_m H)}{\partial t} + \frac{\partial(\rho_m u_j H)}{\partial t} = \frac{\partial}{\partial x_j}\left[\frac{k_{eff}}{C_{pm}} \frac{\partial H}{\partial x_j}\right] + Q'''$$

Energy Equation – Energy Form

$$\frac{\partial(\rho_m T)}{\partial t} + \frac{\partial(\rho_m u_j T)}{\partial t} = \frac{\partial}{\partial x_j}\left[\frac{k_{eff}}{C_{pm}} \frac{\partial T}{\partial x_j}\right] + \frac{Q'''}{C_{pm}}$$

Combining all above three equations, a General Transport Equation generated.

$$\frac{\partial(\rho_m \Phi)}{\partial t} + \frac{\partial(\rho_m u_j \Phi)}{\partial t} = \frac{\partial}{\partial x_j}\left[\Gamma_{eff} \frac{\partial T}{\partial x_j}\right] + S_\Phi$$

A fundamental method for numerical simulation of governing equation is the finite-difference of finite-element approximation. Involving the methods follow four steps.[22]

i. The domain of problem is covered by a simple mesh.
ii. Values of the numerical solution are labelled at the intersection or nodes of mesh.
iii. A finite difference of finite-element approximation to the differential equation is formulated in each node resulting in a system of algebraic finite-difference of finite-element equations
iv. The system of equations approximating the problem is solved to produce a numerical solution. This process generally involves solving numerically large systems of linear algebra equations and the corresponding computer algorithms.

The turbulence modeling is implemented as a closure model for the Reynolds stress with the most commonly used k-ε turbulence model being.

k-Equation

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + D - \rho\varepsilon$$

$\varepsilon -$ Equation

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + C_{1\varepsilon}\frac{\varepsilon}{k} - C_{1\varepsilon}\frac{\varepsilon^2}{k} + S_\varepsilon$$

In an industrial combustion process generally there are three combustion models

a. Non-Premixed Combustion: Fuel and oxidizer come in separate streams. Convection or diffusion of reactants from either side into a flame sheet takes place. Turbulent eddies distort the laminar flame shape and enhance mixing.
b. Premixed combustion: Fuel and oxidizer are already mixed at the molecular level prior to entry into system & ignition. Rate of propagation (flame speed) depends on the internal flame structure. Turbulence distorts the laminar flame shape and thus accelerates flame propagation.
c. Partially Premixed combustion: Reacting systems with both non-premixed and premixed fuel/oxidizer streams.

The Composition PDF Transport model is used to incorporate finite-rate chemistry in turbulent flames. The PDF (Probability Density Function) represents the fraction of time that the fluid spends at each species, temperature and pressure state. The mean reaction rate can be calculated from the PDF as:

$$\overline{\dot{w}_k} = \int_0^\infty \int_0^1 \dots \int_0^1 \dot{w}_k P \, dY_N \dots dY_1 \, dT$$

The Non-Premixed Combustion model is followed with some assumptions [23, 24].

– Equal species diffusion coefficients

– Unity Lewis number

– Low Mach number flow

The governing transport equations for species mass fractions and enthalpy reduce to identical advection - diffusion equations. The solution to all of these equations can be obtained from a single partial differential equation in terms of a conserved scalar variable. The transport equation for the mean mixture fraction is readily derived from the species equation under the assumption of equal diffusivities and single fuel and oxidizer streams.

$$\frac{\partial}{\partial t}(\rho f) + \frac{\partial}{\partial x_i}(\rho u_i f) = \frac{\partial}{\partial x_i}\left(\rho D \frac{\partial f}{\partial x_i}\right)$$

The assumption of equal diffusivities is reasonable because at high Re, turbulent diffusion overwhelms laminar diffusion and turbulent eddies convect species (more or less) equally. The Mean mixture fraction is calculated from

$$\frac{\partial}{\partial t}(\rho \bar{f}) + \frac{\partial}{\partial x_i}(\rho u_i \bar{f}) = \frac{\partial}{\partial x_i}\left(\frac{\mu_t}{\sigma_t} \frac{\partial \bar{f}}{\partial x_i}\right) + S_m$$

Mixture fraction variance from

$$\frac{\partial}{\partial t}\left(\rho \overline{f'^2}\right) + \frac{\partial}{\partial x_i}\left(\rho u_i \overline{f'^2}\right) = \frac{\partial}{\partial x_i}\left(\frac{\mu_t}{\sigma_t} \frac{\partial \overline{f'^2}}{\partial x_i}\right) + C_g \mu_t \left(\frac{\partial \bar{f}}{\partial x_i}\right)^2 - C_d \rho \frac{\varepsilon}{k} \overline{f'^2}$$

For fuel stream mean fraction is put **One** and for oxidant stream is **Zero**. There is no need to select the species for the equilibrium calculation, the user defines the "boundary" species, and the "excluded" species. The equilibrium solver automatically adds any other species in equilibrium. Temperature limits are calculated automatically, the only inputs is the minimum temperature. The number of species in the PDF table determines only the species that are available for post processing, not the species that take part in the equilibrium computation. The PDF Table is created as a Non-Adiabatic Steady Flamelet table.

CFD analysis of heat transfer in freeboard of rotary kiln was done with licence version of ANSYS 13.0, authorized by NIT Rourkela. ANSYS 13.0 is an engineering simulation software (Computer-Aided Engineering) developer that is headquartered in Canonsburg, Pennsylvania, United States. The company was founded in 1970 by Dr. John A. Swanson and originally named Swanson Analysis Systems, Inc. Ansys has acquired a number of companies since 2000, including ICEM CFD Engineering, CADOE, CFX (2003), Century Dynamics, Harvard Thermal, **Fluent Inc**. (2006) and Ansoft Corporation (2008). Its code is based on the Finite element method and is capable of performing static (stress) analysis, thermal analysis, modal analysis, frequency response analysis, transient simulation and also coupled field analysis. The Ansys multi physics can couple various physical domains such as structural, thermal and electromagnetics. Many researchers and engineers prefer this module because of its parametric language known as Ansys Parametric Design Language (APDL). The APDL allows users to execute all the commands required to pre-process, solve and post process the problem, from a separate text file known as macro.

CHAPTER 06

MODEL DEVELOPMENT

As explained in Chapter 4,Rotary Kiln, a cylindrical vessel, inclined slightly to the horizontal. It is the cylindrical reactor inside which iron making process occur. A typical 500TPD capacity plant Kiln is **80 m in length** and having **4.34 m inner** & **4.85 outer diameter** which rotates around its own axis a speed of 0.6 to 2.0 rpm. The basic components of a rotary kiln are the shell, the refractory lining, support tyres and rollers, drive gear and internal heat exchangers. At its discharge end a central lobe blower is attached to for flame development and stabilization of temperature profile inside of kiln. The Lobe blower has a central oil gun for initial firing. It gives both axial and radial proliferation to blown air into the kiln. As schematically represented in Fig. 6.1.. Beside the central blower a coal throw pipe is introduced into the kiln for slinging of pulverized coal.

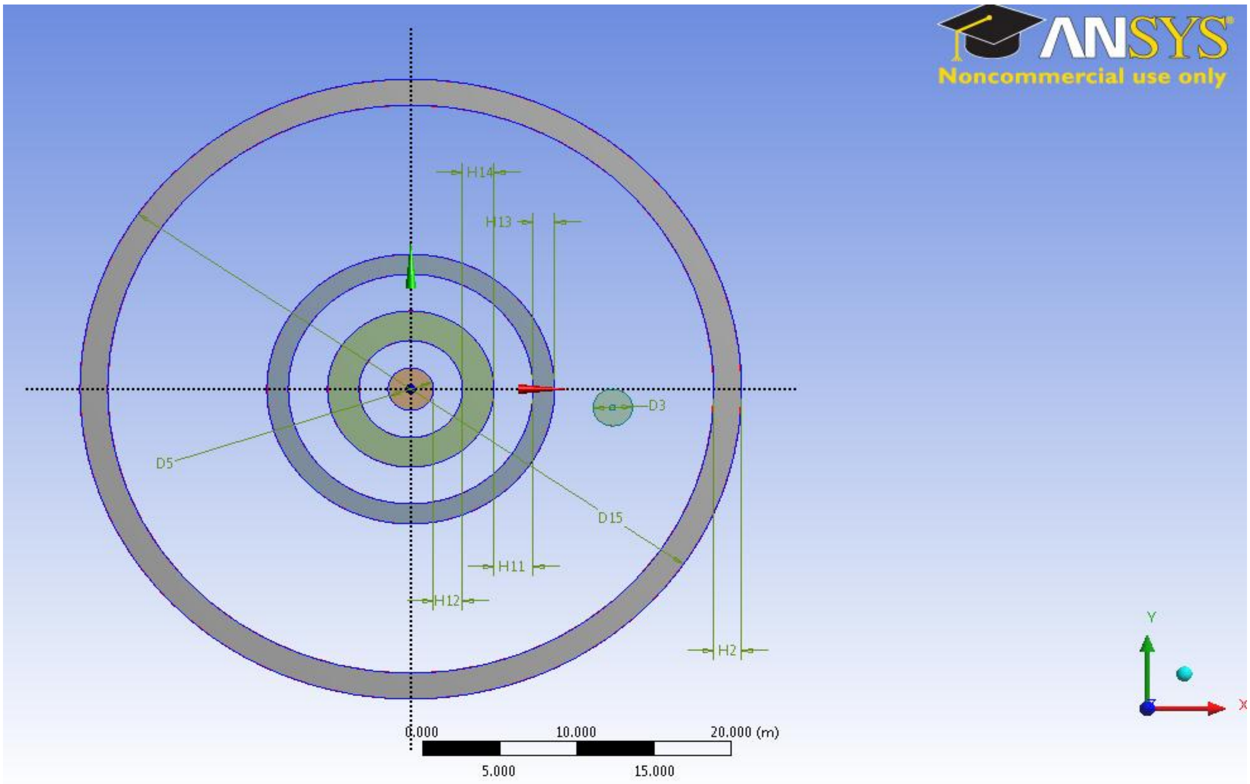

Fig. 6.1 Schematic Drawing of discharge end of Kiln

Some of the abbreviates and their specifications in figure 6.1 are

H2 : Thickness of Kiln Shell Wall with refractory having thickness 0.255m.

D15: Internal Diameter of Kiln, 4.34m.

H13: Thickness of outer wall of Lobe blower, 25mm.

H11: Annular Space for Axial air flow, 100mm.

H14: Thickness of inner wall of Lobe blower, 50mm.

H12: Annular Space for Radial air flow, 50mm.

D5: Diameter of oil gun, 20mm.

D3: Diameter of coal throw pipe.

Both Two-Dimensional and Three-Dimensional virtual configuration of Kiln were developed by Design Modeller of **ANSYS 13.0**. Two-Dimensionally inside of kiln represented by a rectangle having length *80m*. is represented in X-axis and kiln inner diameter *4.34m* in Y-axis. Whereas the Three-Dimensional configuration of Kiln was developed as solid cylinder having length *80m* and diameter *4.34m.* Both Two-Dimensional and Three-Dimensional profiles are shown in Fig.6.2.

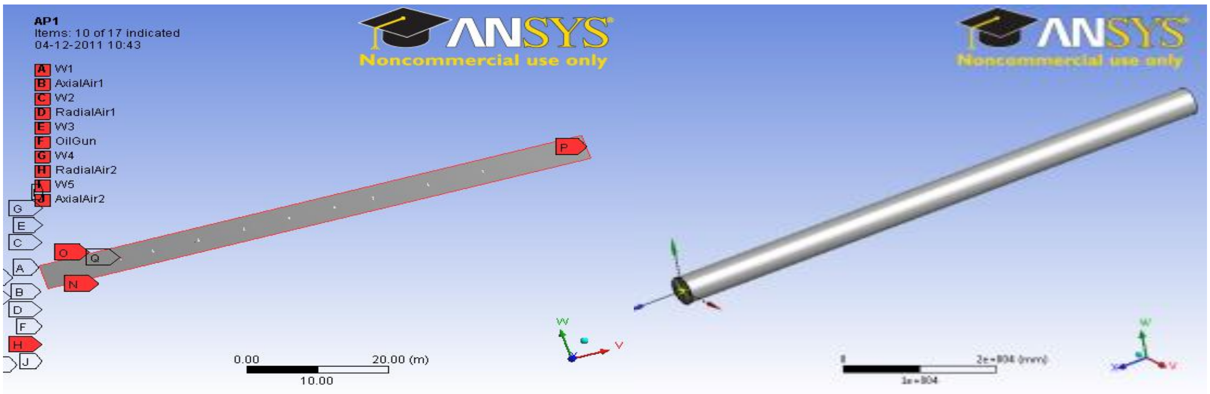

Fig.6.2: 2D & 3D model of Sponge iron Rotary Kiln

To facilitate the function of lobe blower to kiln similar faces for material input were developed by method of **Face imprint** with **Protrude** operation.

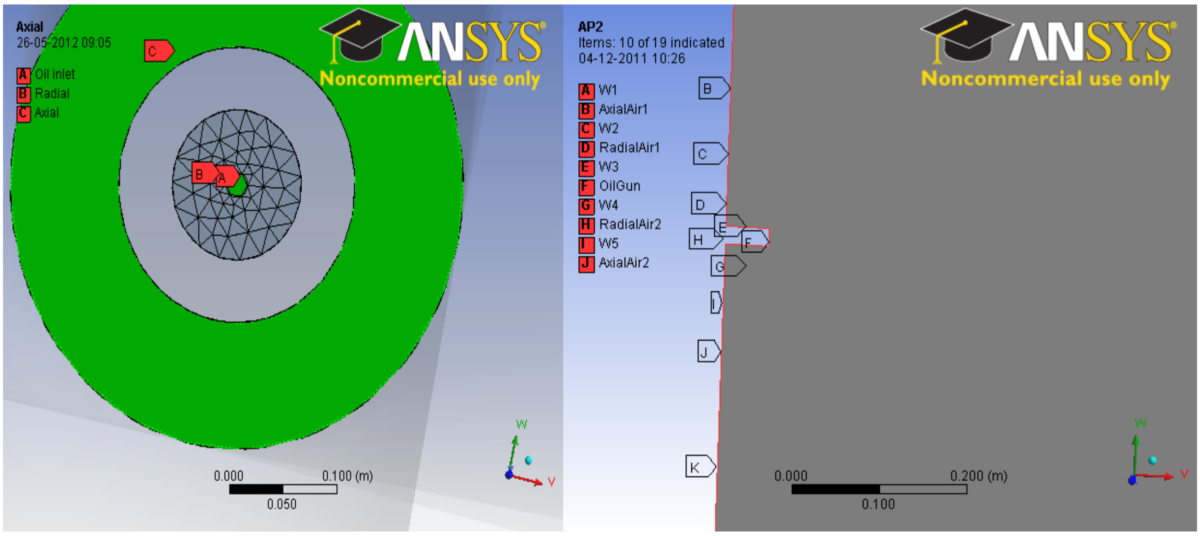

Fig.6.3: Faces of lobe blower.

In The exit face of Kiln a **Kiln Burner** face introduced. Burner face has a diesel firing point of radius *20mm* & advanced by *60mm* inward of kiln.. A cut for The generated faces made in 2D are shown in Fig.6.3: Lobe blower faces of kiln. **Oil Gun** is surrounded by a secondary air(**Radial Flow**) inlet. Radial air inlet has a space of *50mm*. Secondary air path is separated by a wall of *50mm* thickness from Primary Air(**Axial air**) inlet. A face of **Coal Through Pipe** was made on exit face. Coal Through pipe is *585mm* away and *18mm* below the centre of kiln. Nearly 20% of kiln volume cut from the bottom to make it a separate body.

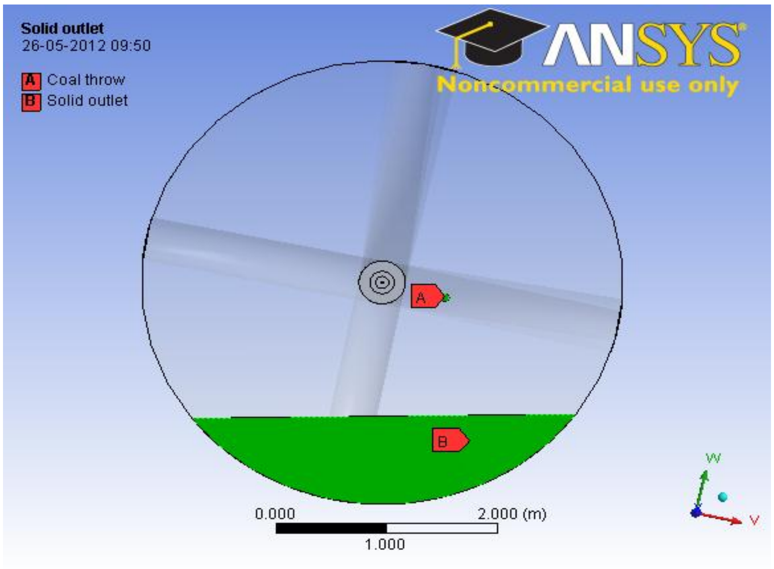

Fig. 6.4: Coal throw and solid out face at discharge end of kiln.

This lower part of kiln represents the solid bed of kiln as shown in Fig. 6.4. With the help of **Share Topology** tool and **Part** tool both bodies converted into **One Part Two Bodies** mode.

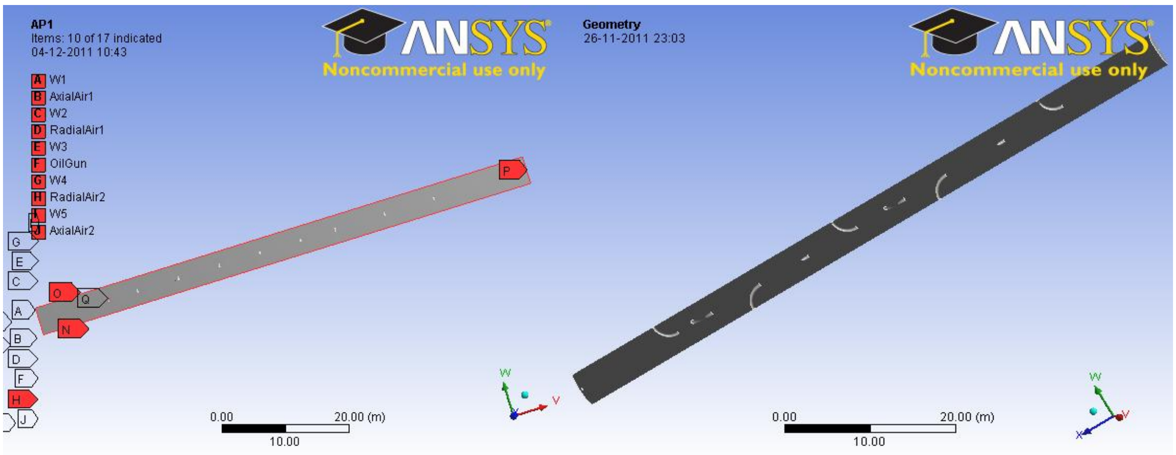

Fig. 6.5: Cuts made to represent air pipes.

There are nine air tubes installed across the length of kiln. Air tubes are separated at distances of 8.1, 8.1, 5.7, 6.7, 6.7, 6.7, 6.7 & 4.6m. from the feeding end to discharge end of kiln respectively. In case of 3D circular bend holes were made as insertion of air pipe whereas rectangular cuts were made on the surfaces of 2D structure as shown in figure 6.5. The surface of air pipes were defined as wall and the faces toward the inlet end as air blowing face as shown in fig. 6.7 and Fig. 6.8.

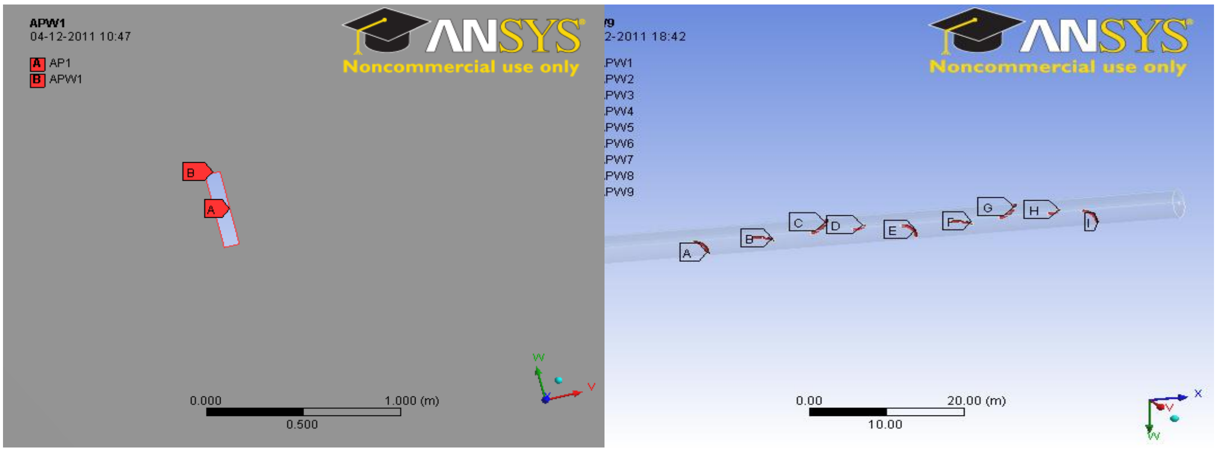

Fig. 6.7: Wall of air pipe.

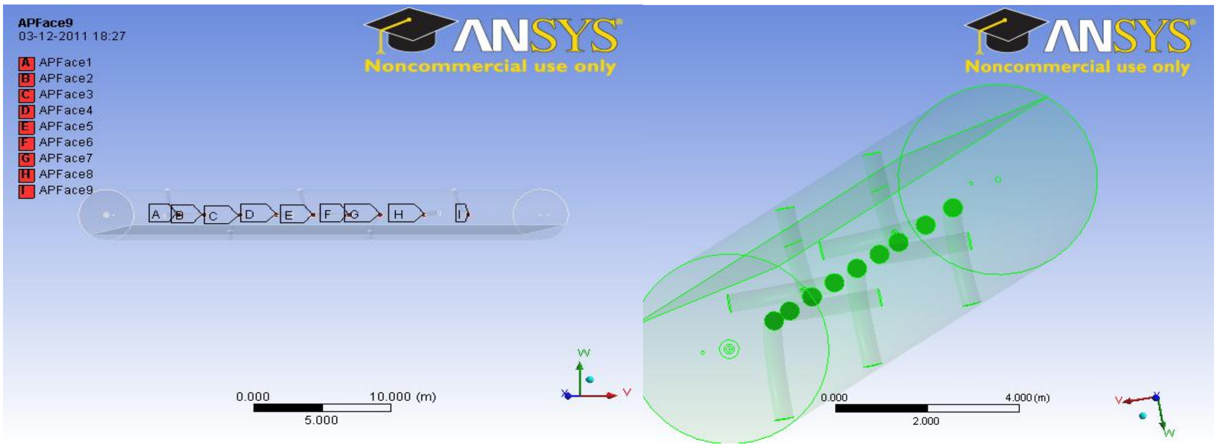

Fig. 6.8: Face of air pipe.

After development of Two-Dimensional and Three-Dimensional virtual configuration of Kiln, the **Geometry** subjected to meshing by **Meshing** tool. The specifications of meshing for 3D are **Physics Preference**: CFD, **Solver preference**: Fluent, **Advance size function**: *On; Curvature*, **Relevance Centre** : *Fine*, **Smoothing** : *Medium*, **Transition**: *Slow*, **Span Angel center**: *medium*, **Curvature normal angel**: Default(45^{o}), **Minimum size**: *0.01m*, **Maximum size**: *0.4m*, **Maximum Face size**: *0.4m*, **Transition ratio**: *0.272*, **Maximum**

layers: *5*, **Growth rate***: 1.2*, **Inflation algorithm**: *Pre*, **Defeaturing tolerance**: *Default(5.0e-3 m*). With this specification a mesh of **62784 nodes** and **337558 elements** generated as shown in fig. 6.9. Mesh of 2D geometry was generated with element size *0.7m.*, transition ratio: *0.272*. This mesh has **72463 nodes** and **71202 elements**. After generation mesh was exported. Modeling of Rotary Kiln needs attention on the control parameters like Feed rates of raw materials.

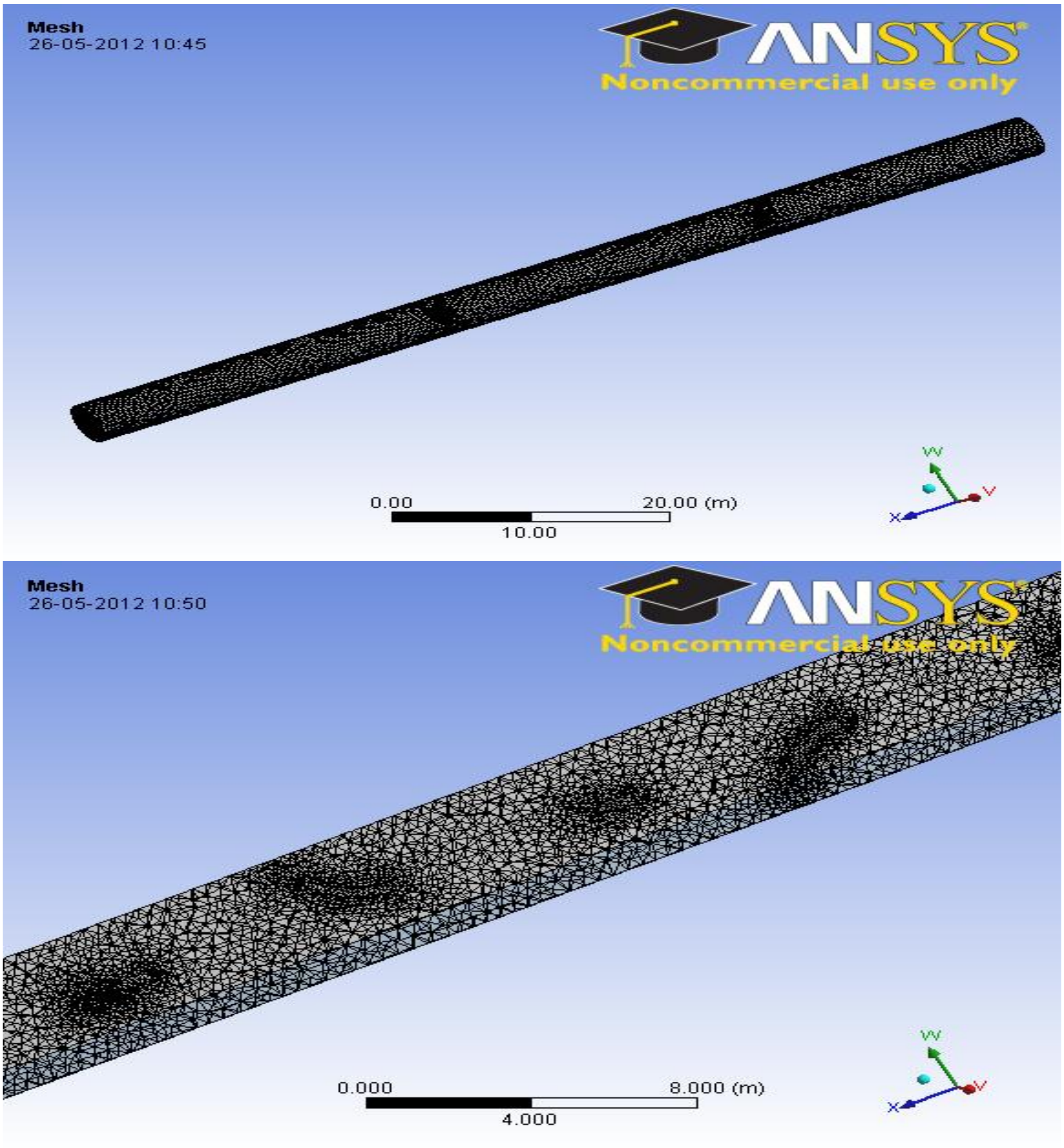

Fig 6.9: Overall view and internal view of generated Mesh.

CHAPTER 07

RESULTS

&

DISCUSSION

After generation mesh with this specification mentioned in above chapter 3D mesh of **62784 nodes** and **337558 elements** and Mesh of 2D geometry having **72463 nodes** and **71202 elements** were exported and saved. In a different **ANSYS 13.0 Work Bench** platform **Fluent** component system was loaded. Fluent set up was started with **Double Precision** option. The earlier saved mesh files were imported into fluent set up to fix the parameters and adopt mathematical models suitable for process specifications.

The **Solver Type** was taken *Pressure Based* and Time in Transient mode. The motion of solid bed in kiln is due to gravity so, **Gravity** was opted. Inclination of kiln by divides the acceleration due to gravity into two Cartesian coordinates. An 5^o inclination to horizontal makes acceleration due to gravity in Y-coordinate 9.77267 m/sec^2 and acceleration due to gravity in Z-coordinate 0.85499 m/sec^2.

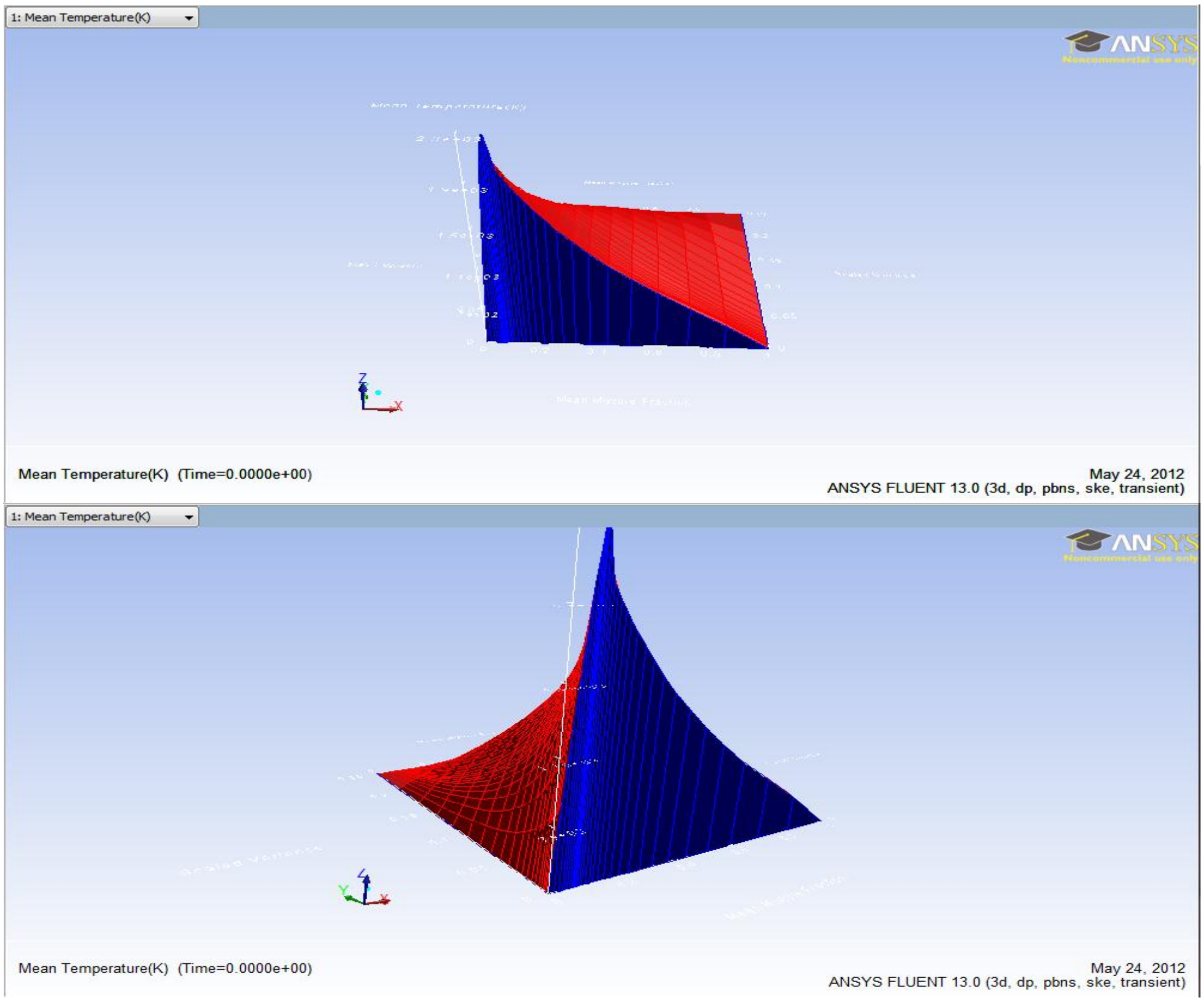

Fig. 7.1: Three Dimensional PDF Table

In Model adaptation **Energy** was made *On*, **Viscous models** of fluids opted with *k-epsilon* (2 equation) model. The *k-epsilon* model was *Standard*. The **Near-Wall Treatment** was taken *Standard Wall Function*. From **Species** dialog box *Non-Premixed Combustion* mode was chosen. **State relation** in *equilibrium* and **Energy state** are in *Non-adiabatic* mode taken. Under **Boundary tab** specifications and composition of both fuel and oxidizing stream were fixed. Under Table tab a PDF(Probability Density Function) Three Dimensional table as shown in fig. 7.1 was generated. The Composition PDF Transport model is used to incorporate finite-rate chemistry in turbulent flames. The PDF (Probability Density Function) represents the fraction of time that the fluid spends at each species, temperature and pressure state.

During modeling of Rotary Kiln needs attention on the control parameters like Feed rates of raw materials and the physical specifications of processing equipment. Some of the basic factors affects the conversion percentage, product quality and feasibility of the process are:

- Temperature profile inside kiln.
- Both primary and secondary Air flow profile inside kiln.
- Kiln revolution.
- Gas pressure in the kiln.
- Cooler discharge temperature.
- Coal Injection rate.
- Mean Particle Size.
- Retention Time.
- Angel of Inclination

Here Air profile is taken as as modeling parameter. As mentioned above the total lobe blown air is divided into two paths with a particular ratio. Simulation with above outcome mesh was done at two values of Axial to Radial volume ratios of 9:1 and 8:2. The outcome of simulation of the two dimensional structure are shown in group of Fig.7.2.

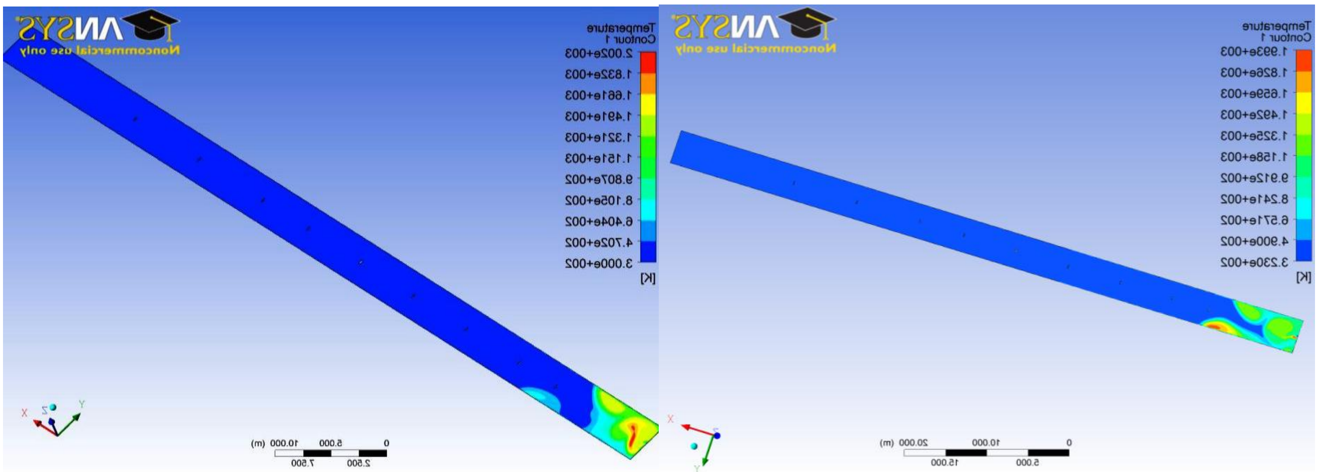

Fig 7.2.A : Temperature profile after 1sec of start up of flow ratio 9:1 & 8:2

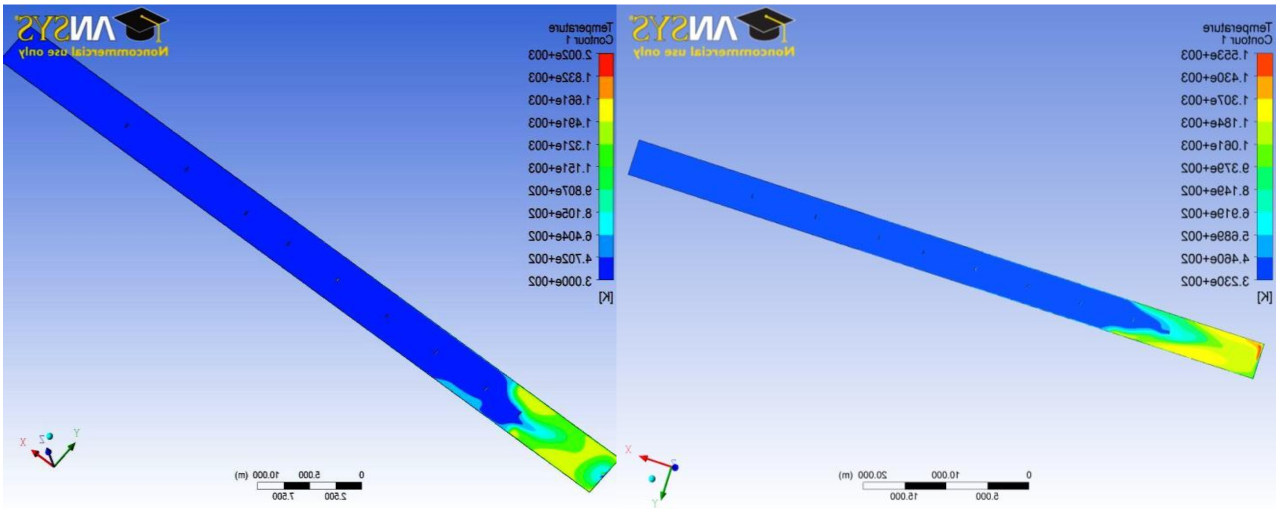

Fig 7.2.B : Temperature profile after 2sec of start up of flow ratio 9:1 & 8:2

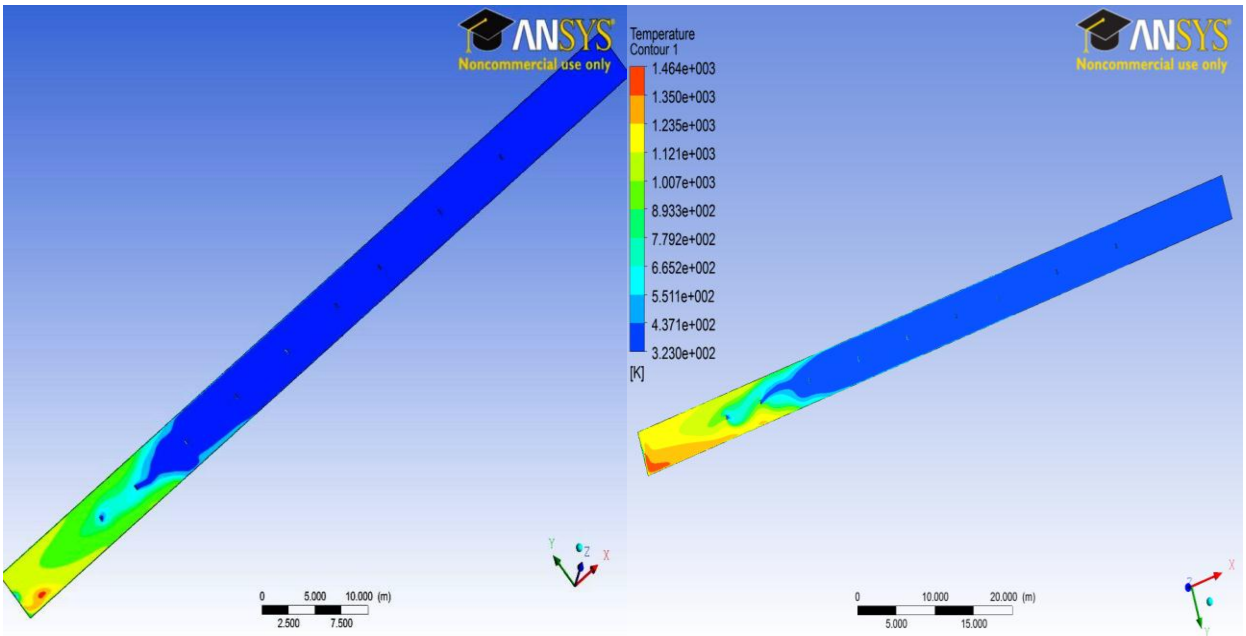

Fig 7.2.C: Temperature profile after 3sec of start up of flow ratio 9:1 & 8:2

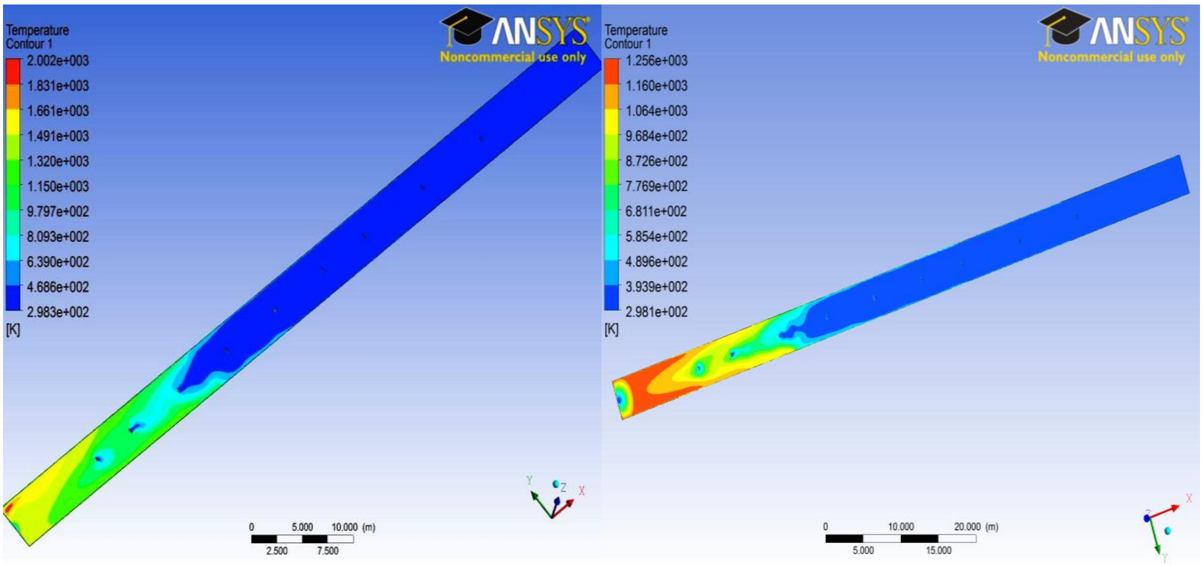

Fig 7.2.D : Temperature profile after 4sec of start up of flow ratio 9:1 & 8:2

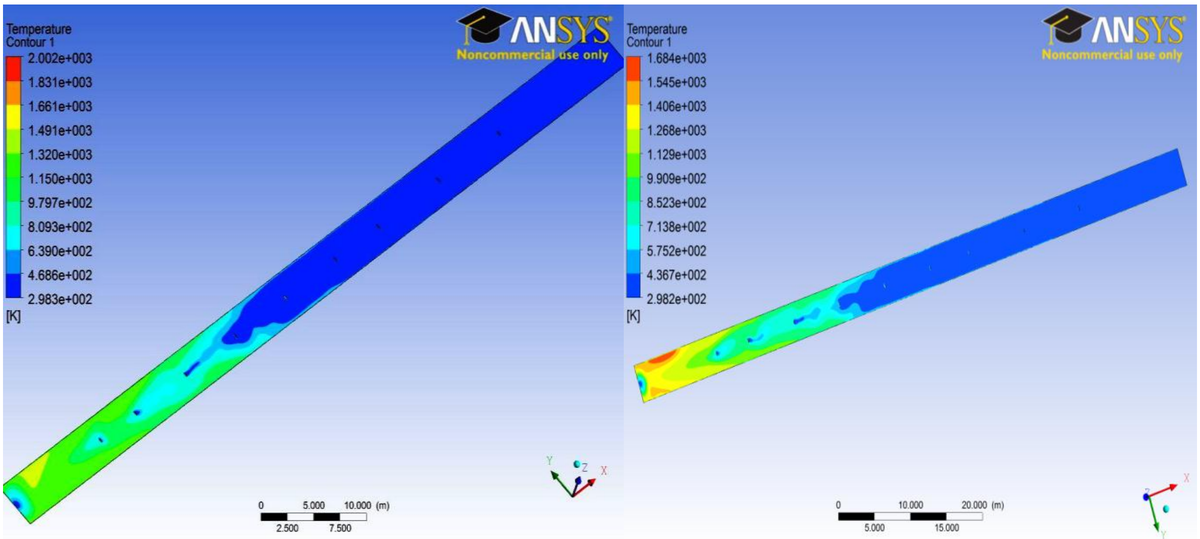

Fig 7.2.E : Temperature profile after 5sec of start up of flow ratio 9:1 & 8:2

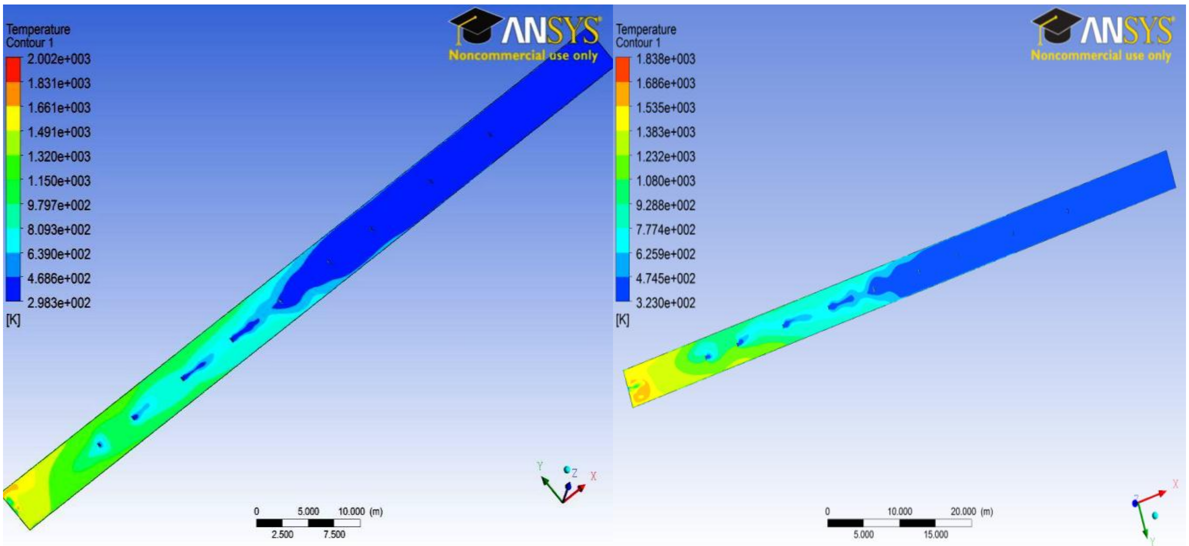

Fig 7.2.F : Temperature profile after 6sec of start up of flow ratio 9:1 & 8:2

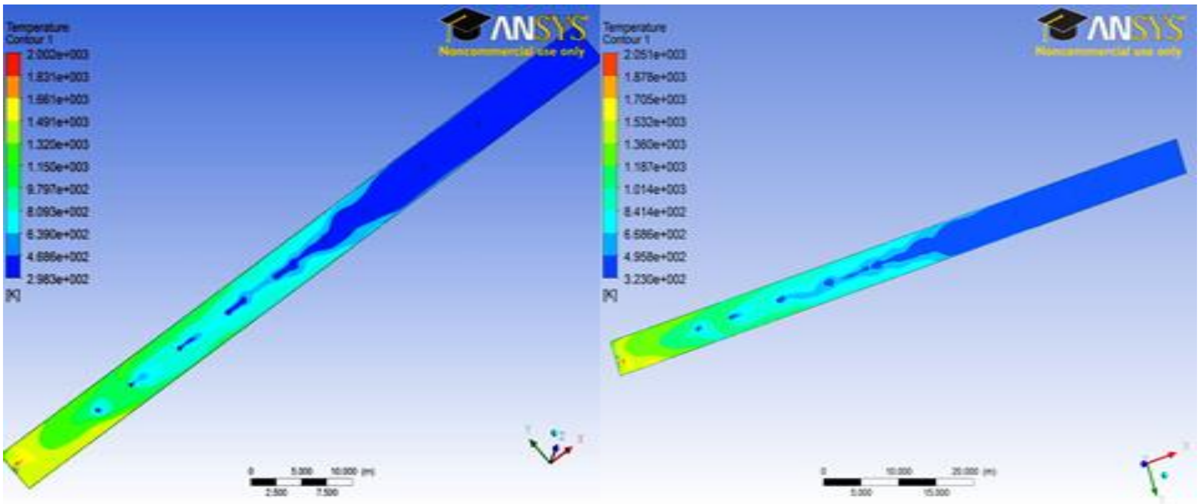

Fig 7.2.G : Temperature profile after 7sec of start up of flow ratio 9:1 & 8:2

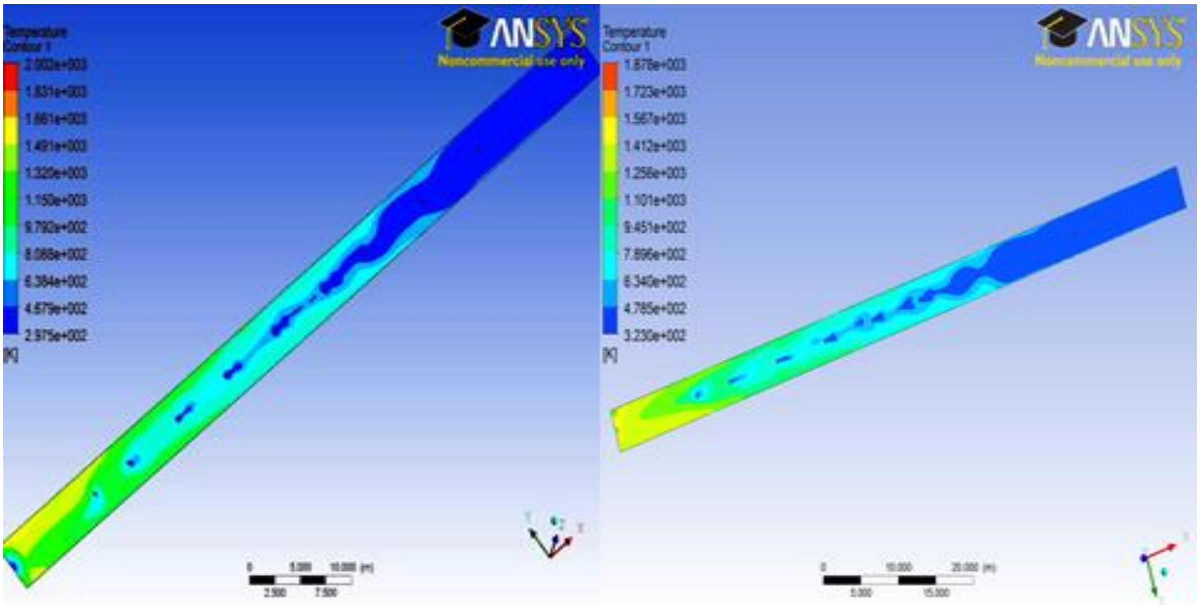

Fig 7.2.H : Temperature profile after 8sec of start up of flow ratio 9:1 & 8:2

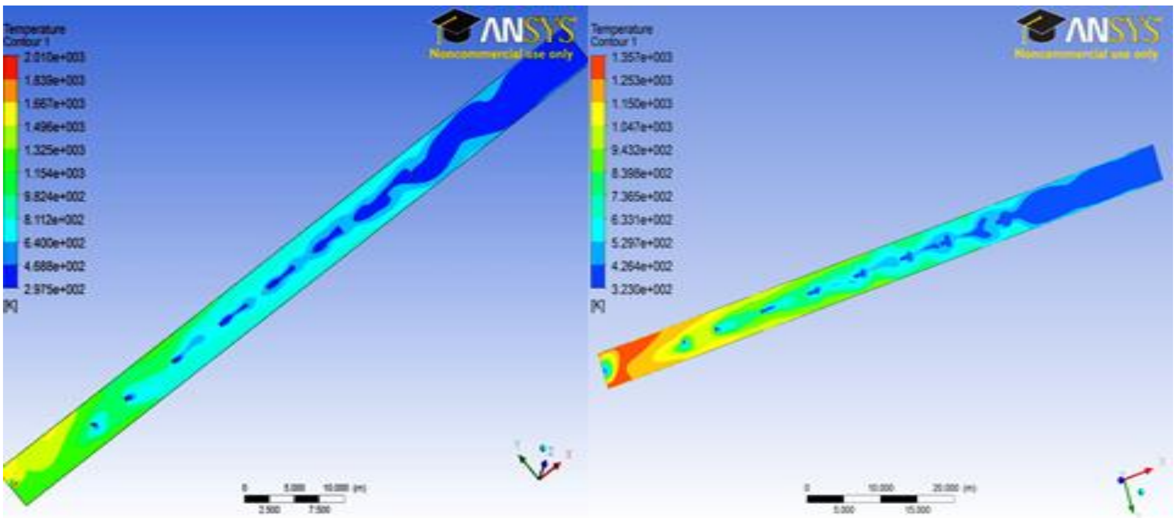

Fig 7.2.I : Temperature profile after 9sec of start up of flow ratio 9:1 & 8:2

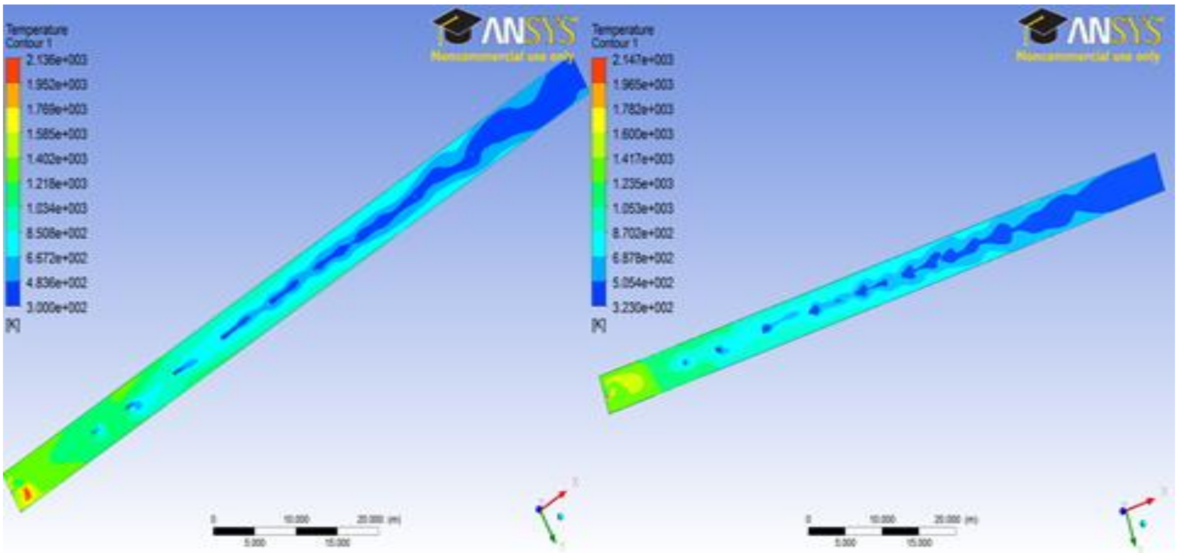

Fig 7.2.J : Temperature profile after 10sec of start up of flow ratio 9:1 & 8:2

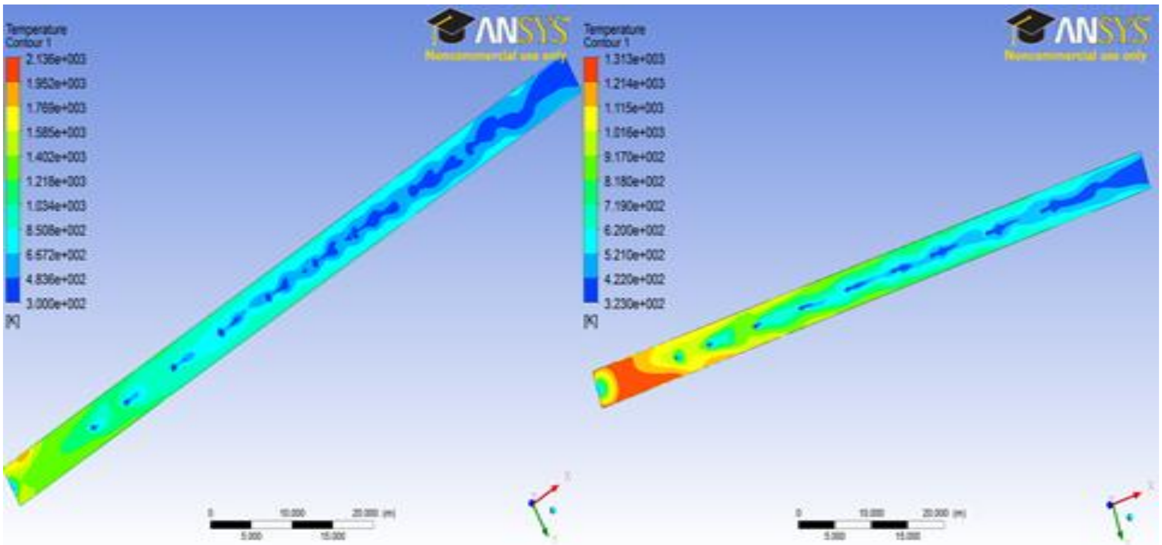

Fig 7.2.K : Temperature profile after 11sec of start up of flow ratio 9:1 & 8:2

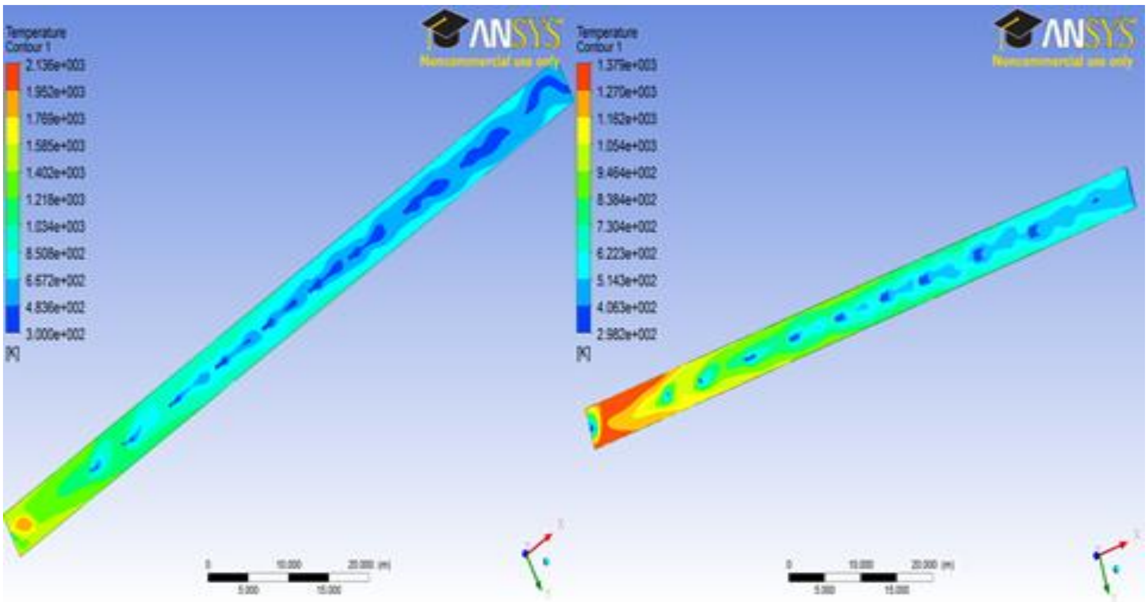

Fig 7.2.L : Temperature profile after 12sec of start up of flow ratio 9:1 & 8:2

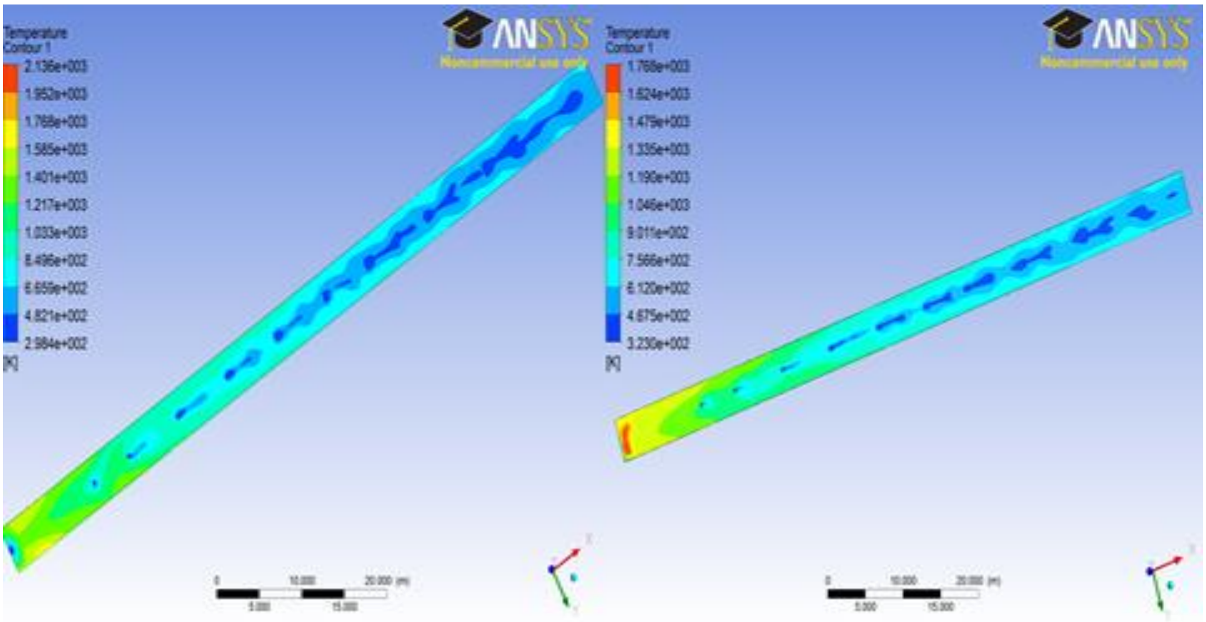

Fig 7.2.M : Temperature profile after 13sec of start up of flow ratio 9:1 & 8:2

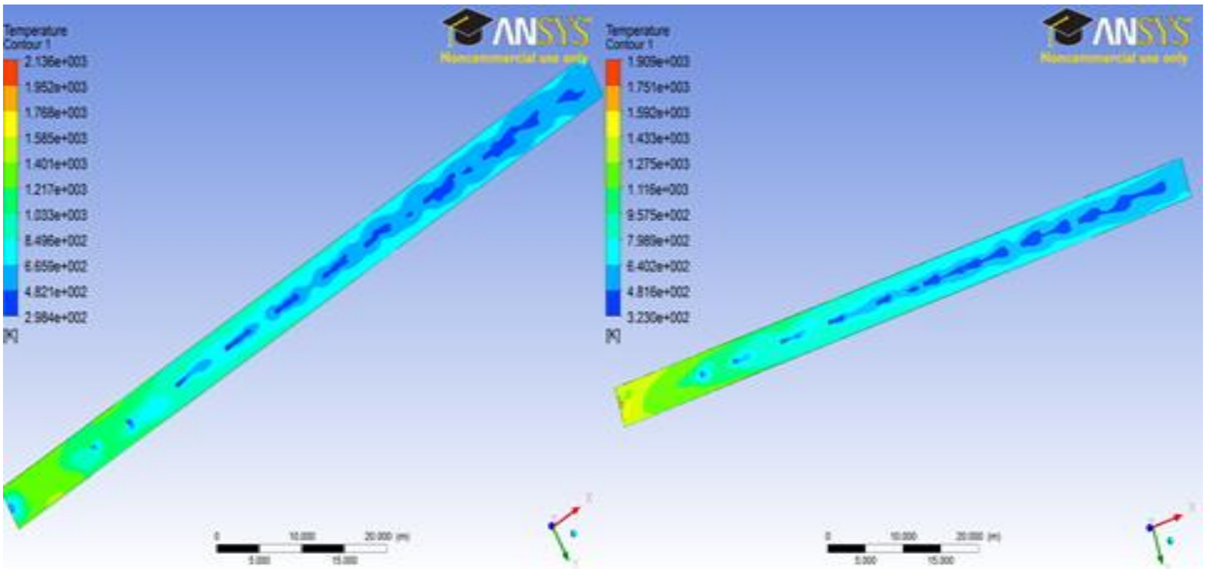

Fig 7.2.N : Temperature profile after 14sec of start up of flow ratio 9:1 & 8:2

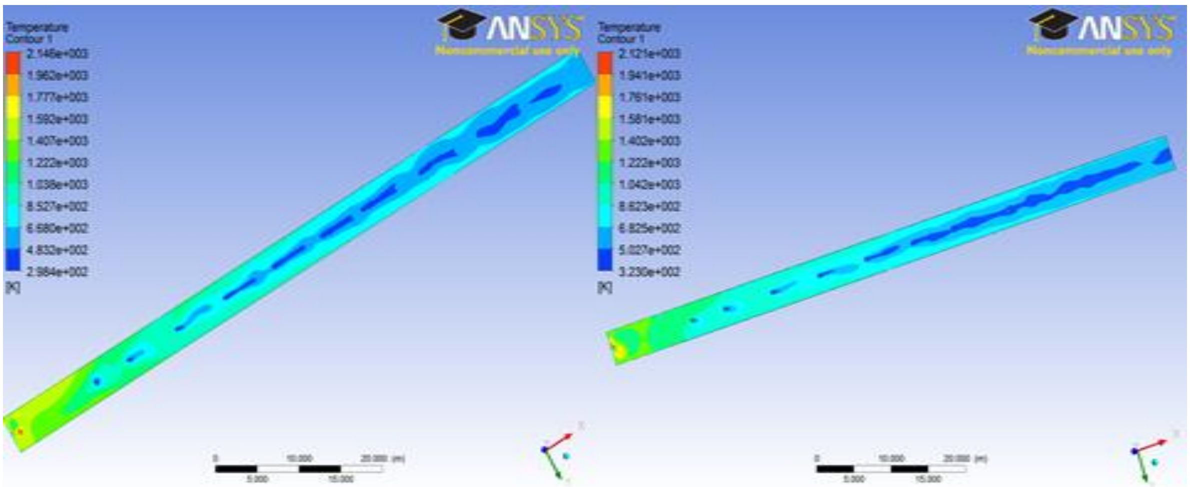

Fig 7.2.O : Temperature profile after 15sec of start up of flow ratio 9:1 & 8:2

Figures in Fig.7.2 group represents the temperature profile of Rotary Kiln. The flame starting from the discharge end of kiln proceeds toward the feeding end of kiln. The flame proliferation is along the direction of air flow in kiln which is opposite the direction solid material flow. As the resulted counter maps shown in fig.7.2 up to 3 seconds from starting both models are showing similar behavior towards temperature rising and temperature proliferation inside kiln. From 4th second to 9th second both models show similar heat proliferation but the temperature rising rate is quite higher with 9:1 flow rate ratio. After 9th second the 8:2 flow rate ratio shows better mixing in freeboard but temperature in 9:1 flow rate ratio still remains higher. At the end of 15th second 9:1 flow rate ratio achieves a better mixing and higher than 8:2 flow rate ratio.

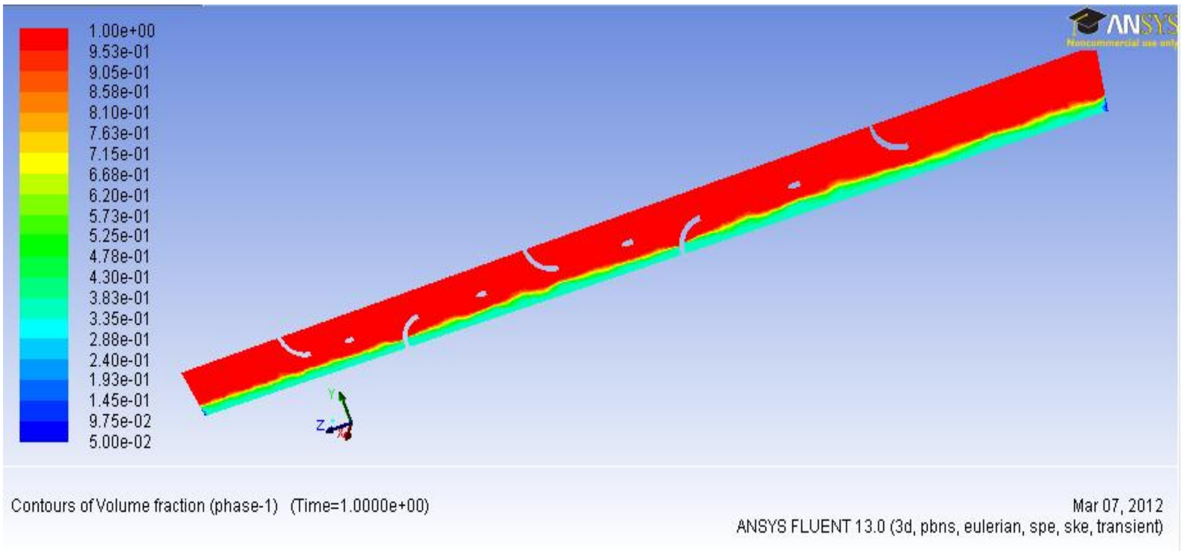

Fig7.3 : Volume fraction of Phase-1(Air)

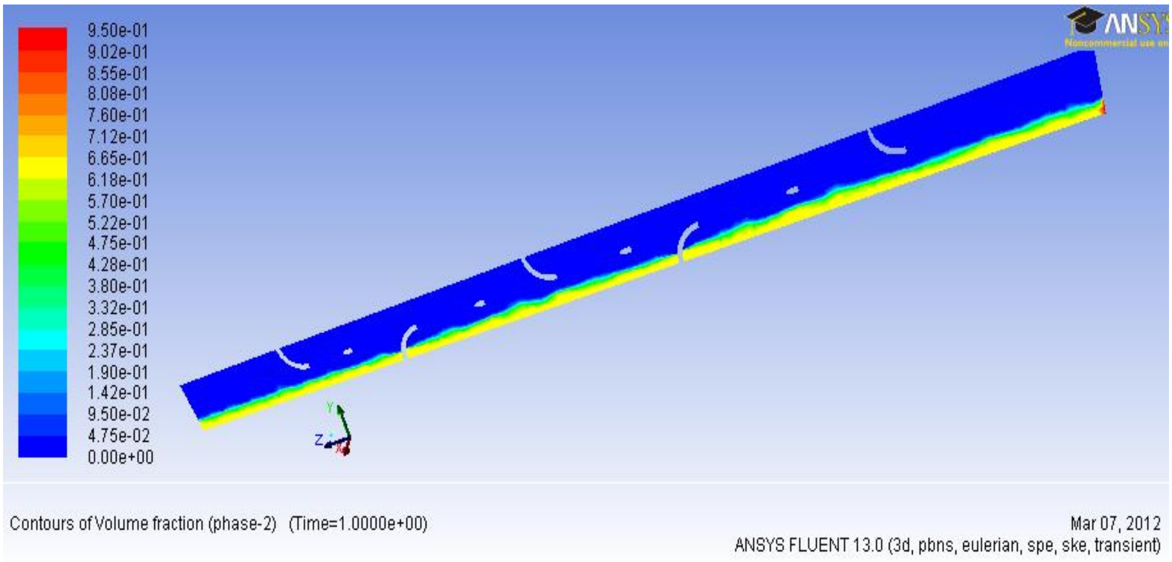

Fig7.4 : Volume fraction of Phase-2(Solid Bed material)

The mesh generated from Three dimensional model imported to Fluent setup with double precision option. The **Solver Type** was taken *Pressure Based* and Time in Transient mode. In Model adaptation **Multiphase** model made on in *mixture* mode. **Energy** was made *On*, **Viscous models** of fluids opted with *k-epsilon* (2 equation) model. The *k-epsilon* model was *Standard*. The **Near-Wall Treatment** was taken *Standard Wall Function*. From **Species** dialog box opened with opting Species Transport model. **Reaction** was activated in *volumetric* with *particle surface*. Though process reactions are occurring in a turbulent environment so **Turbulent-Chemistry Interaction** was set with *Finite Rate/Eddy Dissipation*. Air in kiln was assigned as Phase-1 whereas the solid bed material assigned as Phase-2. Then the model was subjected to simulation. The Fig. 7.3 represents the distribution of air inside of kiln. It is clear from the figure, inside the bed region of kiln a good proportion of air present. This air is the source of oxygen for processing reactions (Direct reduction).

This density difference in solid bed material shown in Fig. 7.4, implies rotation of kiln gives a mixing phenomenon of granular particle present in Solid Bed material. Fig. 7.5 represents the flow direction of granules in kiln due to rotation of Rotary Kiln and Fig 7.6 represents the velocity magnitude of granules in kiln due to inclination.

Fig. 7.5 Velocity magnitude of Phase-2 with respect to Y-coordinate

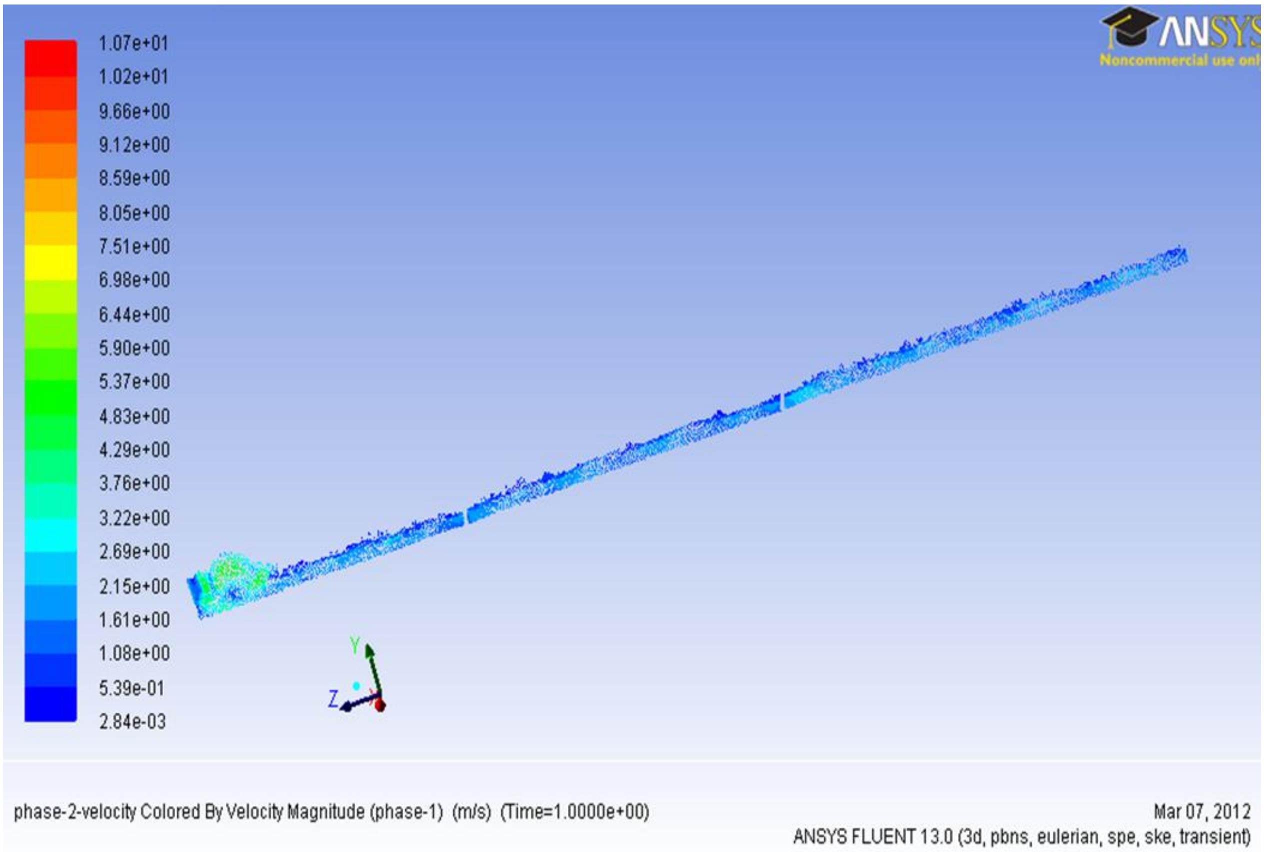

Fig. 7.6 Velocity magnitude of Phase-2

CHAPTER 08

CONCLUSION

Kiln of a typical Sponge Iron producing plant having capacity 500 Tons Per Day was modelled and simulated with CFD package (ANSYS 13.0). This kiln is of length 80m. and inner diameter 4.34m. Kiln was assigned with 9 air tubes to get a maximum turbulence for better temperature profile. A horizontal cross-section of kiln was modelled in a 2D geometry. These air tubes are separated from Inlet end to outlet end at distances of 8.1, 8.1, 5.7, 6.7, 6.7, 6.7, 6.7 & 4.6 respectively. Air flow rate in these tubes 10000 cubic meter/hour. Air flow of 15000 cubic meter/hour mint for central blower spliced into two streams. A larger stream for Axial flow and smaller for radial flow. Axial flow is responsible pushing flame in forward direction. Radial flow pushes the flame in along Y-axis to rise the flame coverage diameter.

Flame profile of kiln was modeled two values of with Axial to Radial volume ratios. Simulated proportions were 9:1 and 8:2. The simulated result of two proportions were compared at various time. From this above result we conclude,

- Both proportions shows similar behavior at starting but the 9:1 proportional flow rate achieves the desired temperature earlier which is similar to the industrial practice. So it is feasible to operate kiln with 9:1 proportional flow ratio.
- Rotation and inclination of kiln causes a proper mixing and flow of solid bed material which are quite essential for the Sponge iron making procedure. Because proper mixing makes better heat distribution in the solid bed material.
- The movement of granules makes them expose to freeboard for direct reduction reaction.
- Downward motion *i.e.* towards the discharge end of granules gives them a suitable residence time for complete conversion and avoidance of reoxidation of sponge iron.

Future Recommendations : On-board heat transfer and reduction reaction occurring in process is to be modelled in a 3D geometry. Pollutant like NO_x, CO_2, CO, Shoot production is also to be determined with this CFD package.

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